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Clean Fuels from Agricultural and Forestry Wastes

Georgia Inst of Tech, Atlanta Engineering Experiment Station

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CLEAN FUELS FROM AGRICULTURAL AND FORESTRY WASTES

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The report gives results of an experimental investigation of the operating parameters for a mobile waste conversion system based on the Georgia Tech Engineering Experiment Station's partial oxidation pyrolysis process. The object of the testing was to determine the combination of parameters producing the most char and oil and the least gas from agricultural and forestry wastes. The tests indicated both the dominant influence of air/feed on char and oil yields, and the desirability of low values of this ratio. In addition to the testing, a preliminary design of a 200 ton/day mobile pyrolysis system for conversion of agricultural and forestry wastes into clean fuels was made and a simplified economic analysis conducted. The results of this work indicate the technical feasibility and the economic profitability of such a system.

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by

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ABSTRACT

An experimental investigation of the operating parameters for a mobile waste conversion system based on the Georgia Tech Engineering Experiment Station partial oxidation pyrolysis process has been made. The object of the testing was to determine that combination of parameters producing the greatest amounts of char and oil and the least gas from agricultural and forestry wastes. From the tests, the dominant influence of air/feed on char and oil yields is apparent and the desirability of low values of this ratio is clear.

In addition to the testing, a preliminary design of a 200 ton/day (assuming a 50 percent moisture feed) mobile pyrolysis system for conversion of agricultural and forestry wastes into clean fuels was made and a simplified economic analysis conducted. The results of this work indicate the technical feasibility and the economic profitability of such a system.

This report was submitted in fulfillment of Project Number A-1653, Contract Number 68-02-1485, by the Georgia Tech Engineering Experiment Station under the sponsorship of the Environmental Protection Agency. Work was completed as of March 1975.

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FOREWORD

This effort was supported by the Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park (IERL-RTP), under Contract 68-02-1485. We wish to express our appreciation to Mr. James Kilgroe and Dr. Max Samfield of IERL-RTP for their many contributions and suggestions. And a special note of thanks is offered to Ms. Eleanor Hancock and Ms. Beth Lanier for their invaluable assistance in the preparation of this document.

It is EPA's policy to report numerical data in metric units. However, for the convenience of the readers, data reported herein is expressed in units normally used in U.S. engineering practice. A table for conversion of these units into the international system of metric units is presented in Appendix D.

SECTION I

CONCLUSIONS

From the results of the testing, the following conclusions can be drawn:

- The effect on char-oil yields of air/feed is very important; the lower the air/feed the greater the yields.
- Bed depth may have an influence on oil yields but little effect on char yields. Thus larger bed depth may be desirable to maximize char-oil yield. (Larger bed depth would also allow use of a minimum number of air tubes and offers minimum obstruction to flow and agitator operation.)
- The effects of agitation (using the particular agitator geometry and feed tested) are not significant in influencing char-oil yields. Agitation would probably allow greater throughputs, however.
- The effect of tube geometry on char-oil yields is apparently not significant.
- The overall mass, energy and chemical balances appear to be satisfactory; thus giving confidence to the results of the testing.

From the results of the design study, the following conclusions can be drawn:

- A 200 ton/day (assuming 50 percent moisture) portable system appears feasible technically, and economically profitable.
- The system economics are strongly governed by the fuel price which can be obtained for the char-oil mixture.
- To obtain a maximum economic benefit, the system should operate 24 hours a day, 250 days a year.
- Credits for disposal make the system especially profitable but are not necessary for economic justification.

- Uprating the system capacity would have a large impact on profit.
- The travel and down time between operations at separate locations have only a minor influence on productivity since typical operations will last two to three weeks.

SECTION II

RECOMMENDATIONS

The results of this study indicate the desirability of proceeding with the development of the mobile convertor concept. More specifically, a study of the effects of scale and of using a different feed material is suggested. Further development work in the utilization of the pyrolysis gases for operating a modified gasoline engine is also felt desirable. More work in the area of mechanical agitation should be made. A test of the burning characteristics of the char-oil mix would be useful. And finally, the design, fabrication and test of the mobile convertor itself is a necessary step before construction of the complete mobile system can be accomplished.

SECTION III

INTRODUCTION

Each year the United States produces hundreds of millions of tons of agricultural and forestry wastes. These wastes, which represent a serious disposal problem, also offer a potential source of a perpetually renewable low sulfur fuel which could be used to help relieve domestic dependence on foreign oil and gas supplies and thereby reduce our severe balance of payments problem. Therefore, if a practical technique for converting even a fraction of these wastes into fuels could be developed, a significant step toward the solution of our nation's energy shortage would be accomplished. On a regional basis, the effect of such a development could be dramatic since there are many areas which would become largely energy self-sufficient if available wastes could be converted into fuels. In addition to the obvious advantages, a program for conversion of wastes into clean fuels could produce an entirely new industry and generate many new job openings in areas presently depressed both economically and technically.

Such an energy development program would provide not only an ecologically desirable method for disposing of wastes and producing fuels, but would avoid the hazards, such as nuclear accidents and oil spills and the unsightly blemishes from strip mining, that are associated with other energy production methods. Because the fuels produced would have a low sulfur content, they could be burned directly or blended with high sulfur coals to produce a low sulfur fuel with emissions acceptable to air quality standards without the need for costly flue gas desulphurization equipment.

There is no doubt that some of the wastes produced are unavailable or unuseable for such a program. This is because, for example, current agricultural harvesting equipment often leaves a large amount of crop residue in the field where it is used as a soil conditioner. While such wastes could be feasibly collected, there is a question as to the desirability of so doing because of the current high cost of fertilizer and the wide-spread depletion of the organic content of our soil. However, much of the wastes are produced at processing plants such as sawmills, sugar mills, rice mills, peanut shellers, cotton gins, etc., which because of the availability and the concentrated form of the wastes, are especially attractive as sources for energy production. It should be recognized that the recovery potential at these sites is based not only upon the annually produced wastes but on the accumulated wastes from many years of prior operation. Indeed, there are canyons filled with wood residue in northern California and individual sawdust piles sixty-feet deep and covering dozens of acres in the Southeast. Therefore, while the total available agricultural wastes are clearly only a portion of that produced, the amounts are none the less staggering and the energy potential is significant in terms of our national energy requirements.

Another concept related to producing energy from wastes is the "energy plantation" (1 - 2) in which "biomass" would be grown entirely for the purpose of producing energy. It has been estimated (1) that an area of less than one third of that involved in farming in the United States could meet the entire energy requirement of all the installed electric generating capacity in the country. The nonagricultural area classified as forest grazing land and grassland ranges, with proper climate and rainfall suitable for energy plantations, is several times that area. Therefore the availability of land for energy plantations is no impediment to its development.

From the above it appears that there is a significant argument that can be made for the production of energy from "bioconversion," whether the energy is a by-product or the principal product of agriculture. However, there are some obvious problems; e.g.:

- Agricultural waste (organic matter) is typically quite wet, containing 30 to 70 percent water and therefore relatively low in heating value per pound.
- Since these materials would be scattered all over the countryside, the transportation costs per Btu to large thermal conversion plants would be very high.
- Because of the water content of these raw materials, the use of existing thermal conversion equipment is doubtful, at least at its rated capacity. Most likely new or modified facilities would be required. (The overall steam side efficiency of boilers utilizing wet organic fuels such as bagasse and bark, is typically 60 to 65 percent. Thus there is a serious conversion penalty using these as-received, wet materials.)
- The particulate emissions from boilers operating on raw organic fuels would likely require the installation of expensive flue gas clean-up equipment.
- Agricultural wastes with a few exceptions are produced seasonally, not continuously. Thus a steady supply of fuel from these wastes is not available and also it is impractical to tie-up capital equipment that cannot be used year round.
- Associated with the construction of a waste conversion facility dependent upon an adjacent, fixed supply of wastes over a long time period are contractual problems between the producer of the wastes and the waste utilizer. While initially the waste producer

> may be spending two to five dollars per ton of raw wastes for disposal, he may hesitate or refuse in a long term contract to give away, or perhaps pay a disposal charge for his wastes. And clearly, once a facility for waste utilization has been constructed, the waste producer, upon termination of the original contract, has the waste utilizer in an uncomfortable economic position.

The above considerations have limited the development of the concept of energy production from agricultural wastes in the past, and unless solutions to the problems described are forthcoming, they will likely curtail future developments. In reviewing these factors, it should be realized that at the heart of the operational problem is the high moisture content of the wastes and the associated high transportation costs. If some means could be provided to eliminate or minimize these problems, then a major step would be taken toward the practical development of the concept.

One apparent solution would be to simply dry the wastes before they are transported; thus avoiding the transportation of all that water. But the question first arises as to the source of energy required to dry the wastes. Secondly is the fact that even wet agricultural wastes are typically quite bulky and drying them will make them even more so. Therefore while the weight of these materials could be reduced by drying, their volume would be hardly affected. Thus the transportation cost benefit would be small or insignificant since the vehicles moving the wastes would be volume limited. Baling these wastes, or compacting them somehow to a greater density is a relatively expensive operation, and not believed to be practical.

Another concept is to utilize a mobile pyrolysis system that could be transported to the site of the waste production and there convert the wastes into a char, an oil and a low Btu gas. The gas could be used to dry the wet feed and to operate the associated equipment and the oil and char could be mixed together to produce a single dense, free-flowing solid.* The weight reduction and the associated transportation costs thereby affected would be very substantial. A further benefit to be derived is that since the system is portable it would provide greater leverage for the waste utilizer in contract negotiations with the waste producer, since the unit could always be moved to a new location. The portability feature would also guarantee greater equipment utilization and through proper scheduling between seasonal agricultural wastes and continuously available forestry wastes could provide an almost constant supply of fuel.

---

*Mixing the oil and char is not an essential step but in many circumstances would be advantageous since it would remove the necessity for a second materials handling system.

Finally, since the portable system could be assembled in factories, using mass production techniques it would likely be less expensive than a comparable fixed installation.

Therefore it appears that the concept of a mobile pyrolysis system has merit, but there are still practical problems associated with operating such a unit in the rural environment. For example, most pyrolysis units emphasize the production of gas, not char and oil; clearly there is little practical use for an intermittantly available low Btu gas out in the countryside. Many pyrolysis units also require expensive front end systems or elaborate auxiliary equipment. And finally most pyrolysis systems operate at elevated temperatures, require expensive insulating materials,and are not easily moved.

The Engineering Experiment Station (EES) at Georgia Tech over the last eight years has developed a simple, steady-flow, low temperature, partial oxidation pyrolysis system which is completely self-sustaining. In the EES design the pyrolysis occurs in a vertical porous bed. A schematic of this unit is shown in Figure 1. From the figure its operating features can be seen. This unit requires no special front end system, has very few moving parts, and depends upon a relatively small blower to provide the air supply necessary to maintain the partial oxidization of the feed. The system typically converts a pound of dry organic wastes into about a half pound of oil and char and one quarter pound of water and one half pound of gas (allowing for the process air itself).

Typically a ton of as-received wastes would be converted, using the EES process, to about 450 pounds of a powdered fuel, similar to coal, with a heating value of 11,000-13,000 Btu/lb. Thus, depending upon the feed moisture content, the energy available for use at the central thermal conversion plant could be 75 to 80 percent of that theoretically available from the original dry waste; and, using a boiler conversion efficiency of 80 to 85 percent, the overall steam-side efficiency of the process could be 65 to 70 percent. Hence the percent of useable energy could be as large as and perhaps larger than that available with direct burning but with avoidance or significant reduction of the problems of:

- Transporting the wastes.
- Modification or construction of new facilities compatible with fuels derived from organic wastes.
- Emissions resulting from unburned fuel particles.

The powdered char-oil fuel could be burned in either suspension fired or in stoker fired boilers with esentially no modification. It could be blended with cheaper high sulfur coal to produce an additional economic advantage. The EES system thus appears to have many features desirable for a portable unit.

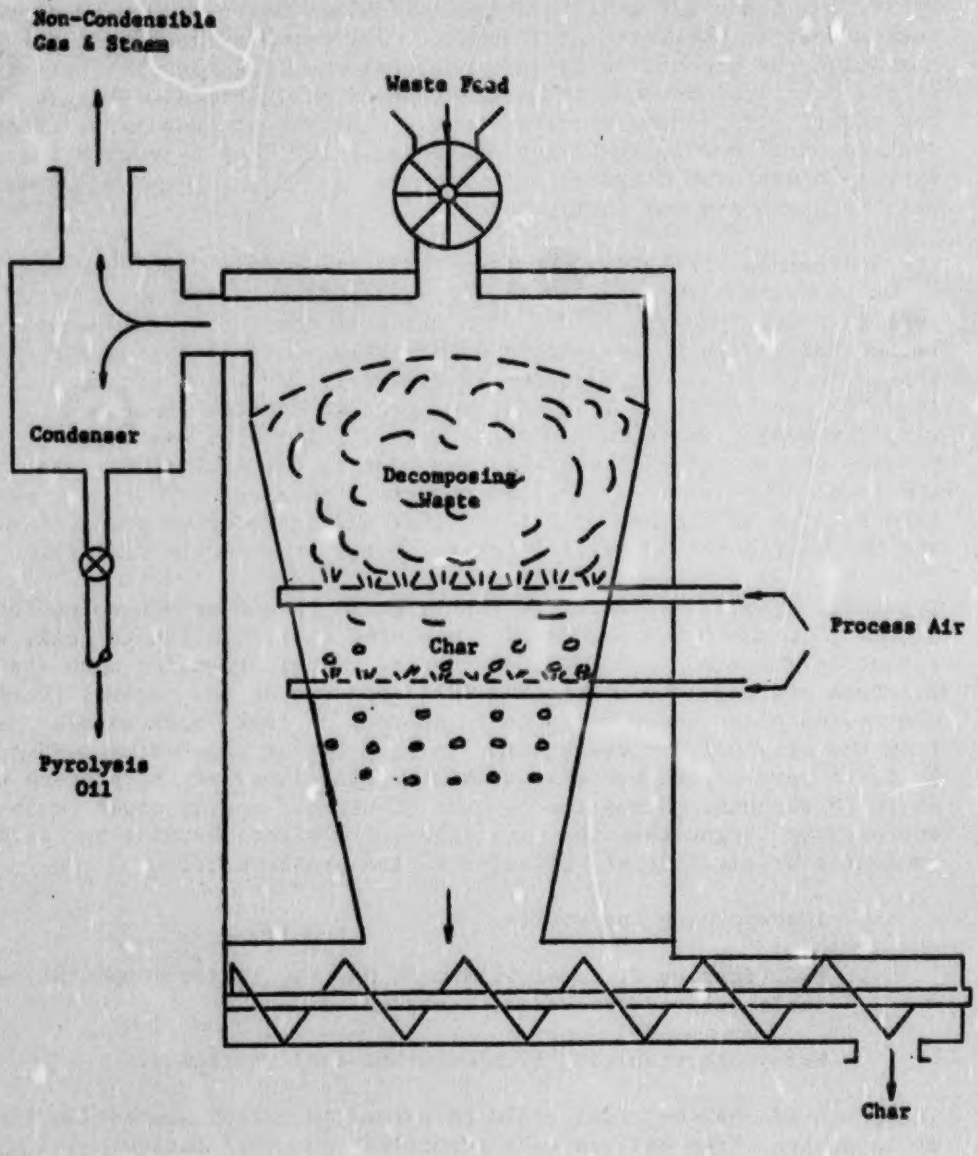

Non-Condensible
Gas & Steam
Waste Feed
Condenser
Decomposing Waste
Process Air
Char
Pyrolysis
Oil
Char

Figure 1

EES Waste Convertor Schematic

This report then describes a program directed toward the development of a portable pyrolysis system for conversion of organic wastes into clean fuels using the EES waste convertor design. The program has two main objectives which are:

1. "to conduct a parametric study of pyrolytic waste convertor performance as a function of system parameters such as feed flow rate, bed depth, air flow rate and air tube location. The purpose of the tests is to optimize the production of char and oil and minimize the production of gas, and to obtain data for integrating the pyrolysis sections with other sections of a portable system.

2. Using the test data obtained, to perform a preliminary design of a transportable agricultural waste conversion system having a nominal feed rate of 200 tons/day, assuming 50 percent moisture."

The report is divided broadly into two sections describing the test program and the design study. However, a brief description of previous EES work in pyrolysis is also presented to put the results of the study in a wider perspective.

SECTION IV

EES EXPERIENCE IN PYROLYSIS

GENERAL

The involvement of the EES in the area of conversion of solid wastes by pyrolysis began with work eight years ago to develop a means to dispose of peanut hulls without producing the pollution problems associated with incineration.

The first pilot plant system, approximately five feet tall, was designed to reduce peanut hulls to a char and a combustible gas. The system built in 1968 was operated on a batch basis at first and then on a continuous basis with a manual input feed. Hundreds of pounds of peanut hulls were converted to char and off-gases during several months of testing with this equipment. Enough data were obtained to demonstrate the feasibility of developing an automated prototype convertor with the vertical, porous bed design.

The large prototype, constructed in 1971 and shown in Figure 2, was built to operate continuously at an input feed rate of 4,000 pounds per hour. The unit was approximately 11 feet in height, and the reaction chamber was mounted on top of a water-cooled collection chamber. The feed-out was accomplished by a horizontal screw at the base of the chamber. The off-gases were treated as potentially explosive in these tests, and consequently, a system was constructed to burn the gases in an unconfined, diffusion controlled flame. Experience with these gases showed that they could be burned easily and safely by premixing and igniting in a conventional fashion. This system was operated over a period of many months, while processing thousands of pounds of feed. The reaction chamber of this convertor was designed to have a minimum weight and only enough operating life to demonstrate the automatic operation of the process. This was done to reduce the overall cost of this experimental prototype. Consequently, the test program started with low temperature operation and on succeeding tests the temperature was raised. The internal structure of the reaction chamber eventually failed after approximately six months

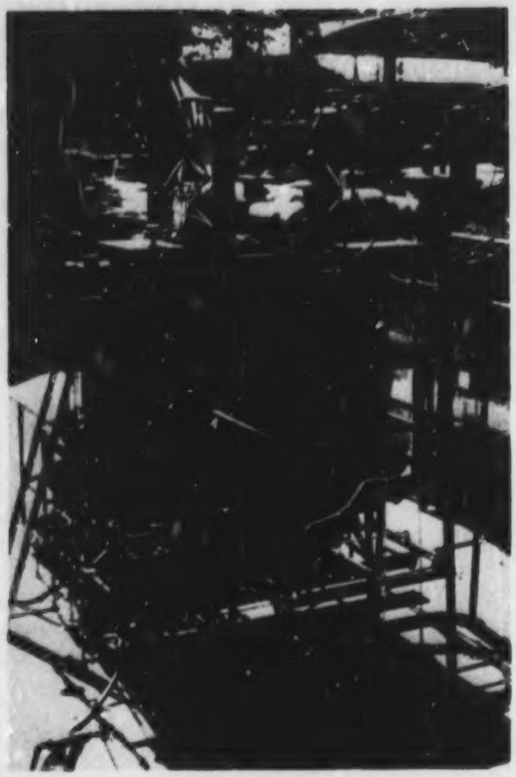


Figure 2. First Generation EES Pyroltic Converter.

of testing as a result of the elevated temperature.

Based on the data and results from the first pilot plant unit and the experimental prototype, an improved pilot plant unit, used in the present study and described in Section V, was designed and built. In addition a large 50 dry ton/day demonstration plant was built by the Tech-Air Corporation, 2231 Perimeter Park, Atlanta, Georgia, who is the licensee for the EES process.

The demonstration plant is located in a wood yard in Cordele, Georgia, and operates on wastes from the sawmill. This system has been in successful operation now for more than three years and was field tested for two years prior to that. The char produced is sold, the pyrolytic oil produced is used in an oil-fired kiln drier, a portion of the gas is used to dry the feed and the remaining gas is flared. Plans are to construct a process steam boiler which will utilize the remaining gases. The system is pictured in Figures 3 and 4. An idea of scale can be obtained by noting the control shed in the lower right hand corner of the overall view, Figure 3. A drier which utilizes hot combustion gases from the off-gas burner reduces the water content of the initially wet wastes down to four percent. The input feed material varies in moisture content from 20 to 55 percent, depending on weather conditions, season of year, and the amount of sawdust in the feed.

Another attractive feature of this system is the cleanliness of its exhaust which is completely invisible to the eye. A recent analysis of the combustion stack gases was made and the results are presented in Table 1. These uncontrolled emissions are lower than existing federal and state standards for incinerators.

Recently, a new, larger (one ton/hour) more sophisticated pilot plant, with improved instrumentation, and located near the smaller EES pilot plant, has been constructed. This system is primarily designed to investigate in greater detail the parameters of the pyrolysis process at a larger scale than previously possible. A photograph of this system is shown in Figure 5.

EXPERIMENTAL WORK

The EES work has involved both laboratory bench scale and pilot plant scale studies of pyrolysis. In both of these complementary efforts, a wide variety of waste materials have been studied.

Laboratory Bench Scale Pyrolysis Experiments

These tests have been made to determine the general feasibility of a particular feed for pyrolysis, to analyze the products, and to determine

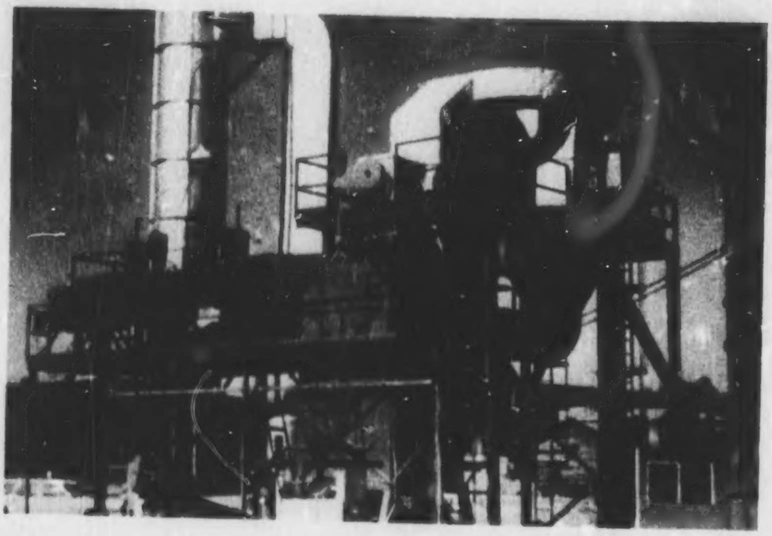


Figure 3. Wood Wastes Field Demonstration Unit--Overall View.

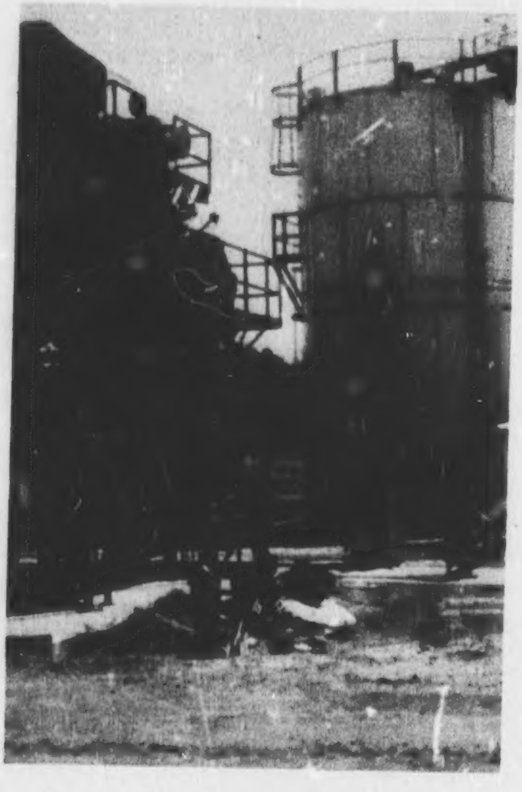


Figure 4. Wood Wastes Field Demonstration Unit--Char Handling and Storage System.

Table 1
Analysis of Combustion Stack Effluent of Wood Wastes

A. COMPONENTS DETECTED

Component	Composition by Volume	Test Method	Mass Rate of Pollutants (pounds/minute)
Water	14%	Liquid Impinger collection	NA[7]
Oxygen	9.0%	GCTC[1]	NA
Nitrogen	69%	GCTC	NA
Carbon Dioxide	7.7%	GCTC	NA
Carbon Monoxide	30 ppm	MSA[2]	6.5×10^{-2}
Particulates	14 micro gms/ft^3	Liquid Impinger collection	9×10^{-4}

B. COMPONENTS TESTED FOR BUT NOT DETECTED

Component	Threshold Sensitivity of Tests[6] (ppm)	Test Method
Hydrogen	0.0009	GCTC
Methane	0.0009	GCFID[3]
Sulfur Dioxide	0.4	MSA[4]
Nitrogen Dioxide	0.04	MSA[5]
Ammonia	0.09	Odor
Hydrogen Sulfide	0.009	Odor

---

[1] Gas chromatography--thermal conductivity detector

[2] MSA--Mine Safety Appliance Co. Test Part No. 91229

[3] Gas chromatography--Flame ionization detector

[4] MSA--Mine Safety Appliance Co. Test Part No. 92623

[5] MSA--Mine Safety Appliance Co. Test Part No. 83099

[6] These components would have to be present in concentration shown to be detected; therefore, these results represent the maximum amounts of these components which could be in the stack gas

[7] NA--Not Applicable

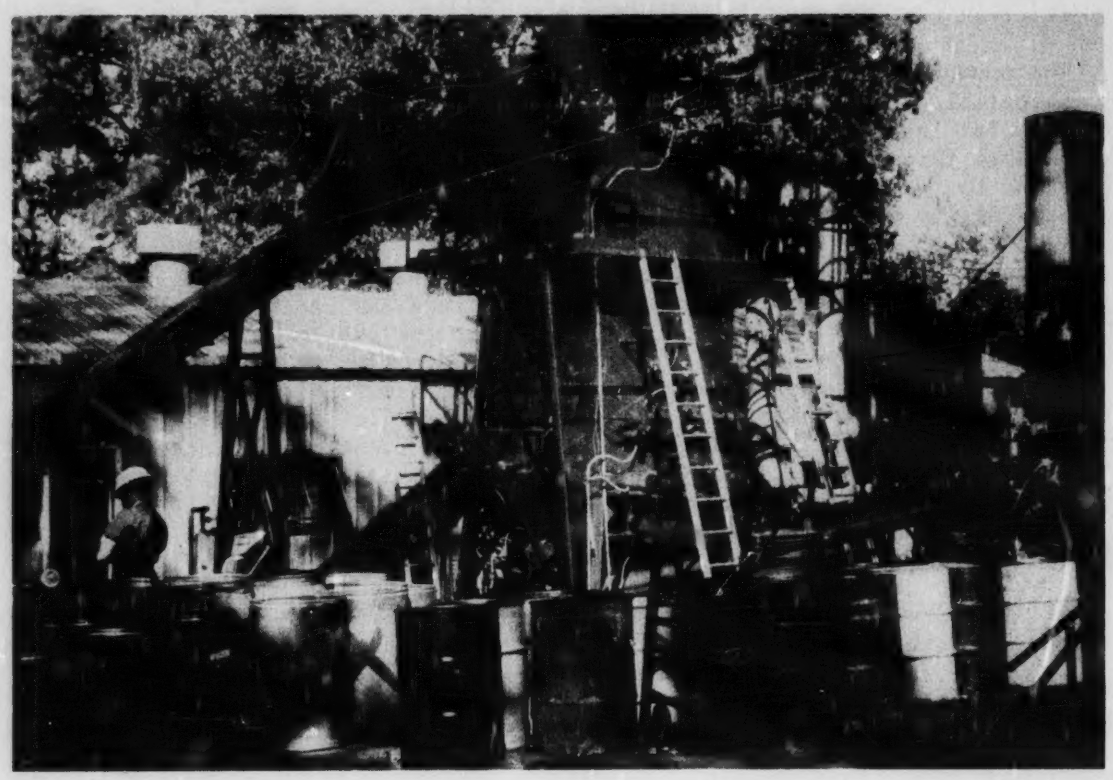


Figure 5. New EES Pyrolytic Converter.

the theoretical yields available. The general technique employed for the pyrolysis of a particular material is as follows: the material to be pyrolyzed is placed in the metal pyrolysis tube either two inches I.D. or six inches I.D. (see Figure 6). The ends are capped, and the closed unit is placed in the appropriate Lindberg tube furnace. The downstream end of the metal tube is connected to a condensation train as shown in Figure 7. The material in the tube is heated to, and held at, the desired temperature for a predetermined time. Spacers inside the pyrolysis tube confine the charge to a uniformly heated zone in the furnace. Internal temperatures are monitored with thermocouples.

The condensation train is arranged so that the high-boiling condensate is collected mainly in one trap, while the water and low-boiling organic material is collected in another trap. The non-condensible gases, after passage through a glass-wool scrubber and a cold trap, are measured with a wet test meter and then collected in a large plastic bag for subsequent analysis by gas chromatography.

On completion of a pyrolysis experiment, the exit from the pyrolysis tube is closed to prevent air from entering the tube and reacting with the hot char while the system cools. After cooling, the system is disassembled, and the char is collected, dried, and weighed. The organic material and water from the condensation train is collected and stored for further analysis. The gas sample is analyzed immediately after collection by use of various gas chromatographic columns and techniques to determine the composition. The pyrolytic gases are predominantly hydrogen, carbon monoxide, carbon dioxide, methane and lesser amounts of gaseous hydrocarbons. The analyses on the char include total ash, acid insoluble ash, elemental composition, volatiles, heating value, and density. The condensible organic material is usually characterized by a determination of percent water, heating value, and elemental composition. Pyrolysis studies have been made with a variety of different materials including pine bark, pine sawdust, mixtures of pine bark and sawdust, cotton gin waste, bagasse, hardwood bark, hardwood chips, peanut shells, carpet waste, nonmetallic automobile waste, municipal waste, dried sewage sludge, and dried chicken manure.

To illustrate the type of results which were obtained from these laboratory experiments, normalized yields (pounds of pyrolytic product per pound of feed) for a mixture of pine sawdust and pine bark are plotted in Figure 8 as a function of temperature. The figure shows that the char yields decrease with increasing temperature, and this can be attributed to the fact that the volatile content of the char decreases as the operating temperature is increased. The non-condensible gases increase with increasing temperature and begins to show a leveling-off at the higher temperatures. This increase can be attributed to the formation of condensible oil from the volatiles liberated from the char as the temperature increases. The aqueous yield decreases with increasing temperature.

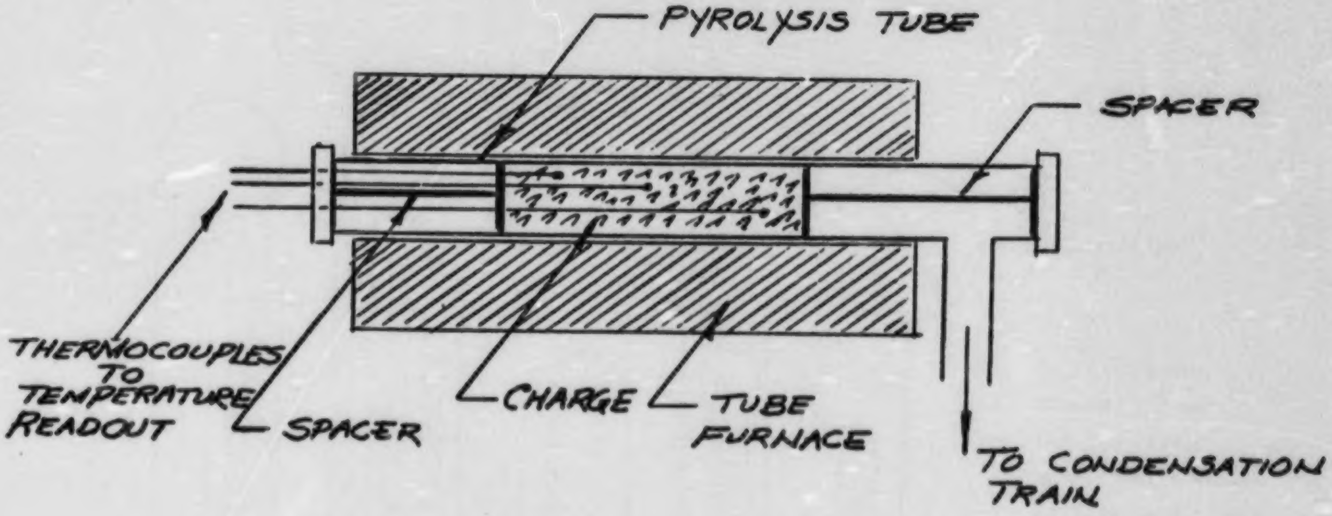

PYROLYSIS TUBE
SPACER
THERMOCOUPLES TO TEMPERATURE READOUT
SPACER
CHARGE
TUBE FURNACE
TO CONDENSATION TRAIN

Figure 6. Pyrolysis Tube Furnace for Bench Scale Experiments

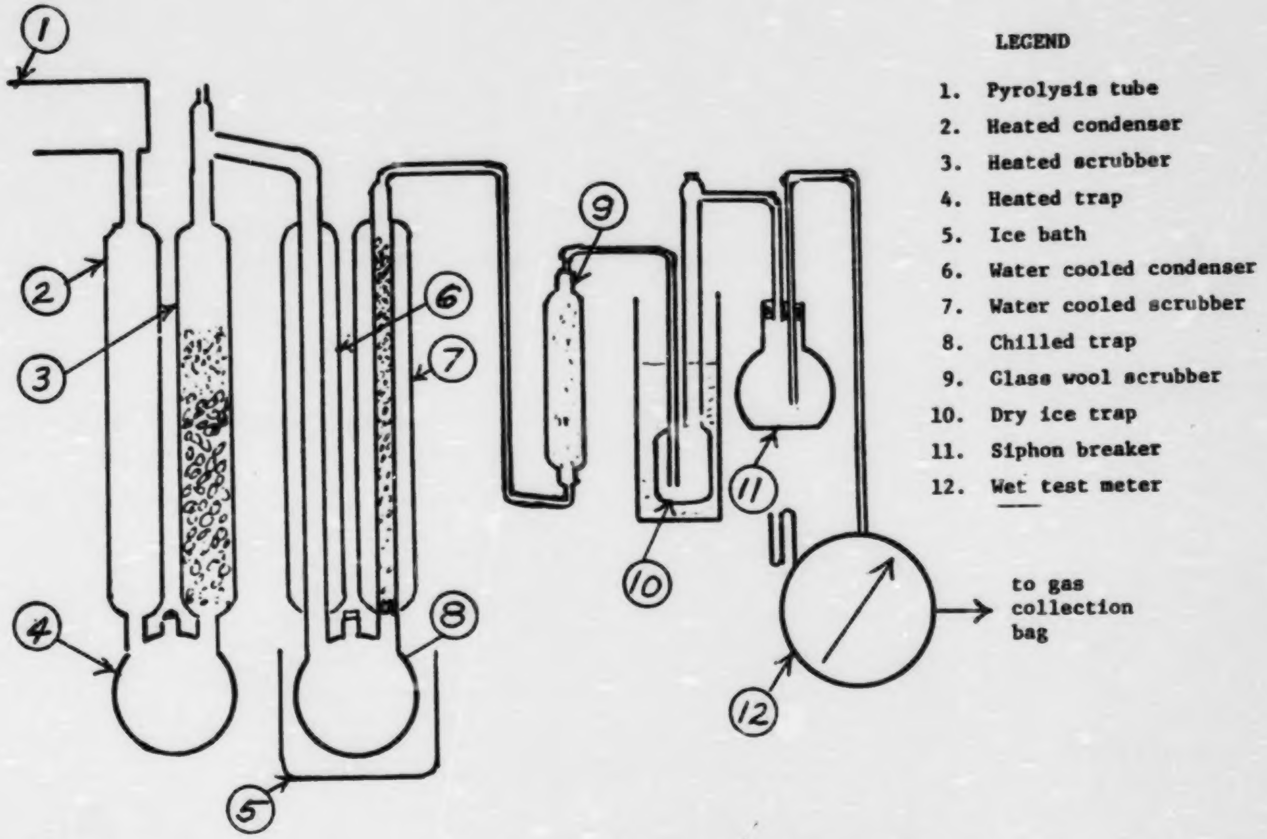

1
2
3
4
5
6
7
8
9
10
11
12
LEGEND
1. Pyrolysis tube
2. Heated condenser
3. Heated scrubber
4. Heated trap
5. Ice bath
6. Water cooled condenser
7. Water cooled scrubber
8. Chilled trap
9. Glass wool scrubber
10. Dry ice trap
11. Siphon breaker
12. Wet test meter
to gas collection bag

Figure 7. Condensation Train for Pyrolysis Experiments

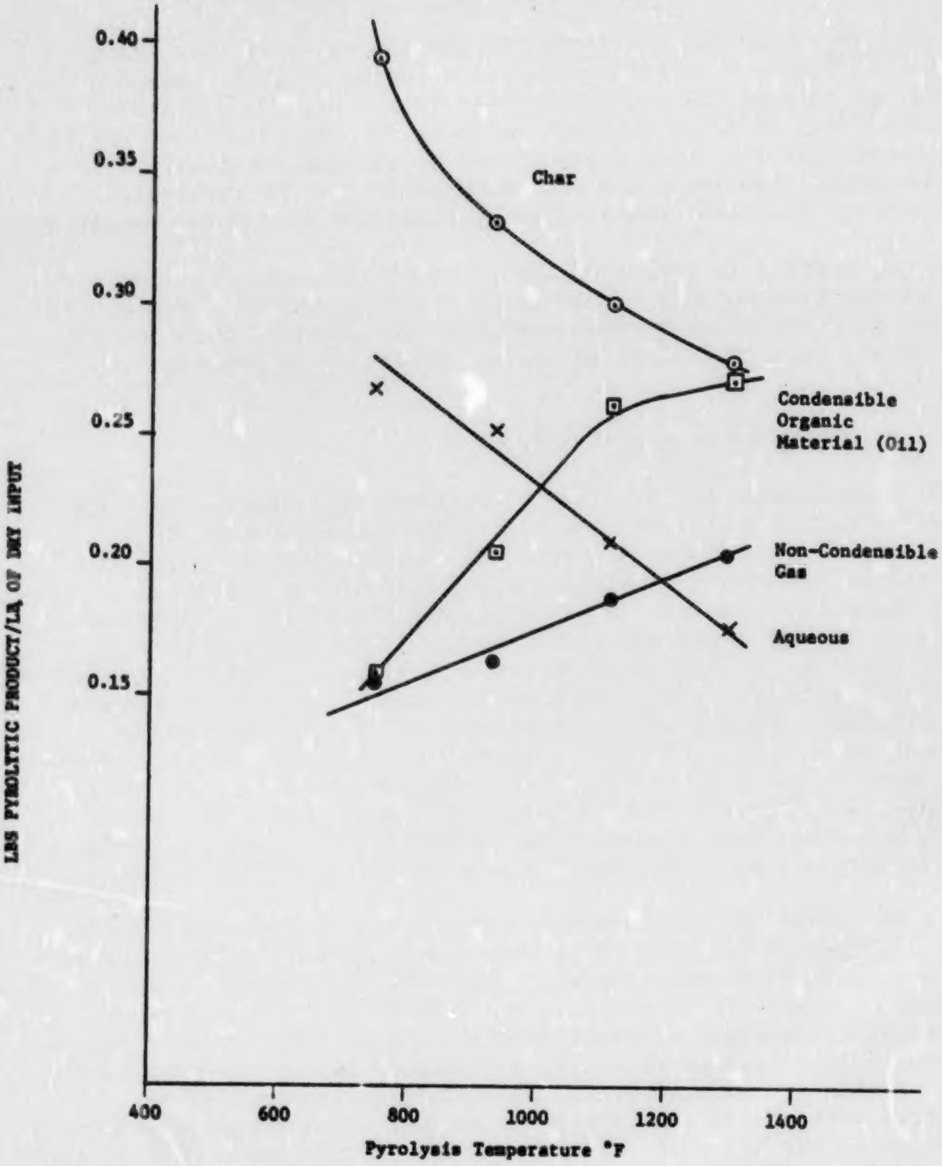


Figure 8. Mass Balance for Pyrolysis of Pine Sawdust and Bark

As the temperature increases, the formation of water is evidently a less dominant reaction while the reaction leading to the formation of more gases and oil became more important. These data are useful in predicting the effects of temperature on yields in pilot plant experimental work.

The heat available from the pyrolysis of pine sawdust-pine bark mixture is presented in Figure 9. The significant information to be obtained from this graph is that the sum of the heat values at each pyrolysis temperature is very close to the heat value of the dry input feed material. These data show that the total heat content of the input material over a fairly wide temperature range can be accounted for in the pyrolytic products (the external heat required to pyrolyze the feed being negligible).

Also shown in Figure 9 is a plot of the ratio of the energy available in a mixture of the char and oil to the total energy in the wood waste. It appears that to recover the maximum energy in the char-oil mixuture the pyrolysis should be conducted at as low a temperature as practical.

Pilot Plant Pyrolysis Experimental Work

The overall objective of the previous pilot plant experimental work has been to determine the operating characteristics and parameters with specific materials. One important question that has been answered with each material is how well the material feeds through the pyrolytic convertor. Many materials are dense enough and are of such a physical shape and size that they are essentially free-flowing and feed easily through the convertor. Some examples are macadamia nut shells, hardwood chips, and pine sawdust. Pine bark must be hogged before it is suitable as a feed material. Peanut hulls, on occasions, have bridged in the convertor and hence some agitation is needed to break the bridge. Other materials, such as bagasse, nonmetallic automobile waste, and cotton gin waste present some problems with feeding. With cotton gin waste, for example, it has been found necessary to use mechanical agitation in the convertor to keep the material from bridging in the pyrolysis zone.

The testing has indicated that the moisture content of the feed material should be less than 10 percent. If the moisture content is in the range of 35 to 50 percent, as is the case with pine bark and sawdust, then the material must be predried. Other data and information obtained from pilot plant pyrolysis experiments include throughput feed rates, yields of char and condensible organic material, and composition of non-condensible off-gases. Ratios of process air to feed material rates are obtained and correlated with yields and quality of products. Materials that have been processed in the EES pilot waste convertor include peanut hulls, pine bark, pine sawdust, mixtures of pine bark and sawdust, macadamia nut shells, nonmetallic automobile waste, hardwood chips, cotton gin waste, and municipal garbage.

In summary, the EES pyrolysis work conducted prior to this study has indicated that there may be material handling problems associated with

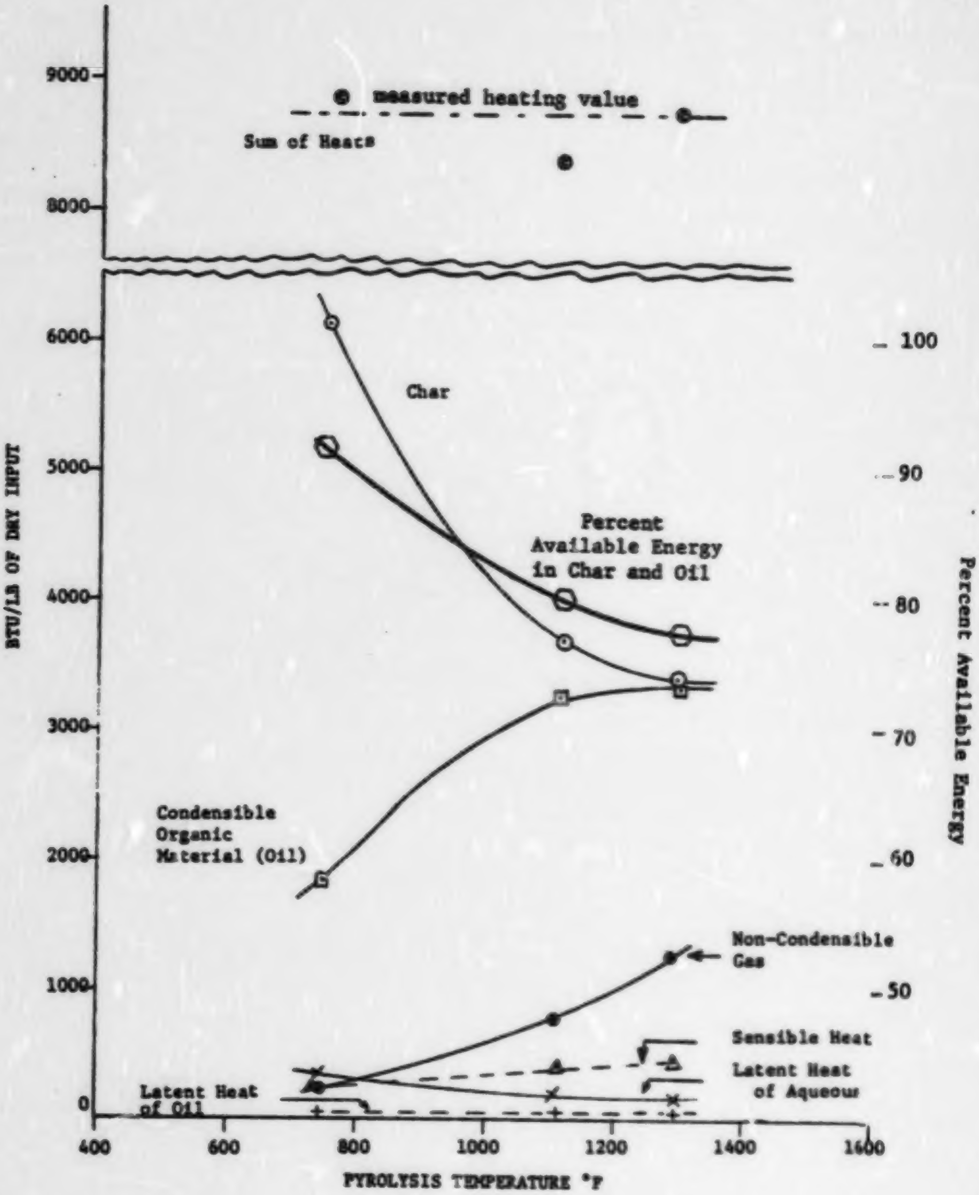


Figure 9. Heat Available from Pyrolysis of Pine Sawdust and Bark

bulky wastes, in which case some form of mechanical agitation may be required. Further, it appears that the pyrolysis temperature has a significant effect on product yields. Since the bed temperature is controlled by the air/feed ratio, it follows that in the pilot plant work this latter ratio should have a major influence on the system output.

SECTION V

TESTING

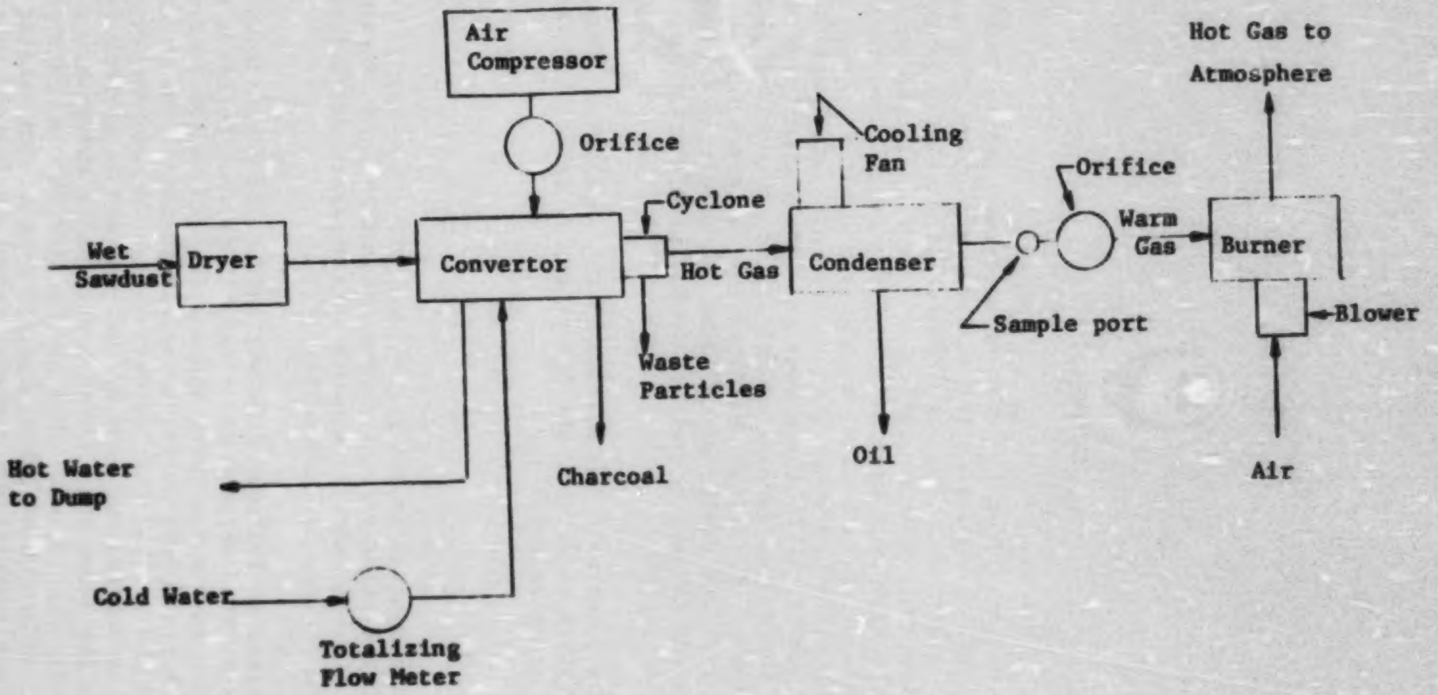
The object of the testing in the current study was primarily to determine the optimum operating conditions for maximum production of char and oil and for minimum production of gas using the EES pyrolysis system. With this in mind, the test instrumentation, the test operation and the selection of the test parameters were made, within practical limits, to shed as much light as possible on those conditions most favorable for application to the portable convertor concept. The primary test parameters were: the air/feed ratio, the depth of the porous bed, the geometry and number of air tubes, and the use of mechanical agitation. A total of 19 runs were made. This included an initial shakedown run, a test run of the effects on production rates and yields of changing the feed from a fifty-fifty mixture of bark and sawdust to pure sawdust, three aborted runs, and fourteen successful runs.

In the following sections a description of the facilities utilized, the test and calibration procedure, the laboratory procedure and the results of the testing are presented.

FACILITIES

The testing was conducted in the six ton/day EES pilot plant. A process flow diagram of the pilot plant is shown schematically in Figure 10. Photographs of the unit showing views of the separate components involved are presented in Figures 11 through 16.

The system operates as follows: the wet sawdust is first dried in a propane fueled crop drier, then weighed and stored in drums. During a test the drums are emptied into a receiving bin and from there the feed passes onto a conveyor which transports it to the pyrolysis unit. The pyrolysis unit is 10 feet tall and is four feet on each side. The average inside dimensions of the bed are two feet by two feet and it is four feet deep. The feed enters the convertor through a gate valve and passes down through the vertical bed. Process air tubes are located in the lower portion of the bed. These water cooled tubes supply enough air to oxidize the feed in their immediate vicinity and thereby produce sufficient heat for pyrolysis of the remaining bed material. The char at the bottom of the


Air
Compressor
Orifice
Wet
Sawdust
Dryer
Convertor
Cyclone
Hot Gas
Waste
Particles
Charcoal
Cooling
Fan
Condenser
Oil
Orifice
Sample port
Warm
Gas
Burner
Blower
Air
Hot Gas to
Atmosphere
Hot Water
to Dump
Cold Water
Totalizing
Flow Meter

EES Pyrolytic Unit Process Flow Diagram

Figure 10

Figure 11. EES Pyrolytic Converter--Feed Bin and Feed Conveyor.

Figure 12. EES Pyrolytic Converter--Close-up of Feed System.

Figure 13. EES Pyrolytic Converter--View of Condenser Train and Afterburner.

Figure 14. EES Pyrolytic Converter--Close-up of Condenser Train and Afterburner showing Particulate Material Separator.

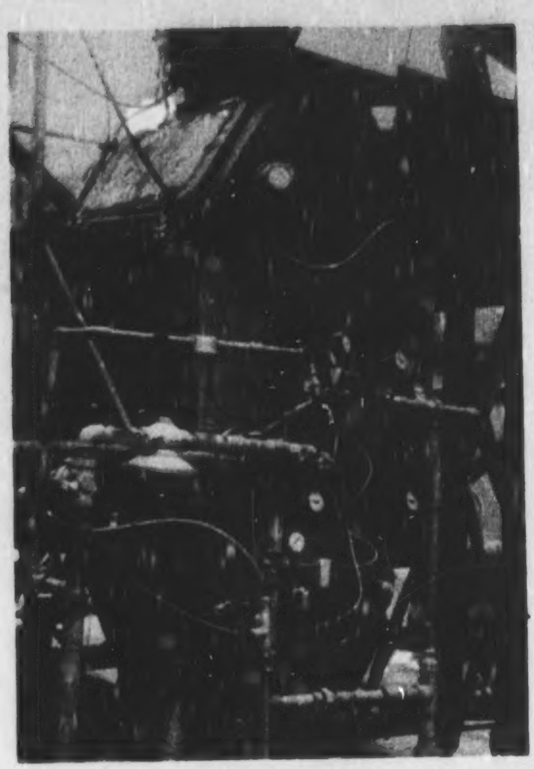


Figure 15. EES Pyrolytic Converter--Close-up of Unit.

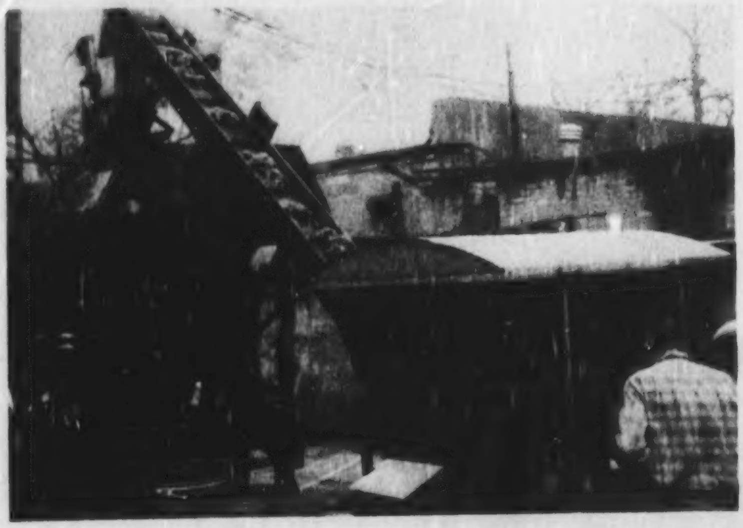


Figure 16. EES Pyrolytic Converter--Feed System Showing Pneumatic Valve.

bed passes into a screw conveyer that transports it to a valve assembly where it is emptied into receiving drums.

The gases produced during decomposition of the feed pass upward through the downward moving feed and leave the unit near its top. The gases then pass through a cyclone where particulates are removed and then to an air cooled condenser which operates at a temperature above the dew point of the mixture. The condenser removes the higher boiling point oils which are collected and weighed. The remainder of the uncondensed oils, the water vapor and the non-condensible gases pass into a vortex burner which incinerates the mixture.

The instrumentation utilized in the study includes:

1. an in situ calibrated orifice to measure process air flow rate
2. an in situ calibrated orifice to measure off-gas flow rate
3. scales used to weigh the dry input feed, the char, and the oil yields
4. a water meter to measure total cooling water flow
5. dial thermometers to measure inlet and exit cooling water temperatures
6. various thermocouples to measure: pyrolysis gas temperatures at several points in the system, internal bed temperatures, external surface temperatures and the vortex burner temperatures
7. a multiple channel recorder to provide continuous data as to various thermocouple outputs
8. a gas sampling system for laboratory analysis of the off-gas composition

The system operates at a pressure of a few inches of water above ambient. Thus there is some gas lost when the inlet feed gate valve operates. As the process rate of the unit increases, the gas production increases and the pressure consequently rises. The unit has pressure relief doors which operate at about 10-12 inches of water. These doors place an upper limit to the allowable processing rate and provide a safe means of relieving overpressures for any system malfunction.

The process rate of the system is governed by the rotational speed of the char output mechanism. A level indicator senses the need for additional feed and activates the gate valve and conveyor system to provide the necessary input. Thus, the gate valve cycles only upon demand, not continuously; hence the gases lost through this valve do not represent a significant energy loss or pollution problem.

The condenser is of a relatively simple design having a series of air cooled vertical tubes through which the hot pyrolysis gases pass. It has been observed that oil droplets are frequently stripped off the inner tube walls by the fast moving gases and carried in suspension through the off-gas system, past the off-gas flow orifice and into the burner. This results in some loss of oil; however, data analysis techniques are used to account for this loss.

In several of the tests a mechanical agitation system was utilized to enhance the flow of material through the waste convertor and to prevent the formation of bridges or arches which can obstruct the downward moving feed. A schematic view of the agitator used in these tests is shown in Figure 17. The system was constructed of heavy walled steel tubing and was water cooled. It was powered by an automatic piston-cylinder system which provided a continuous reciprocating motion. A helical cam provided approximately 150 degree rotation of the agitator on each forward and reverse stroke.

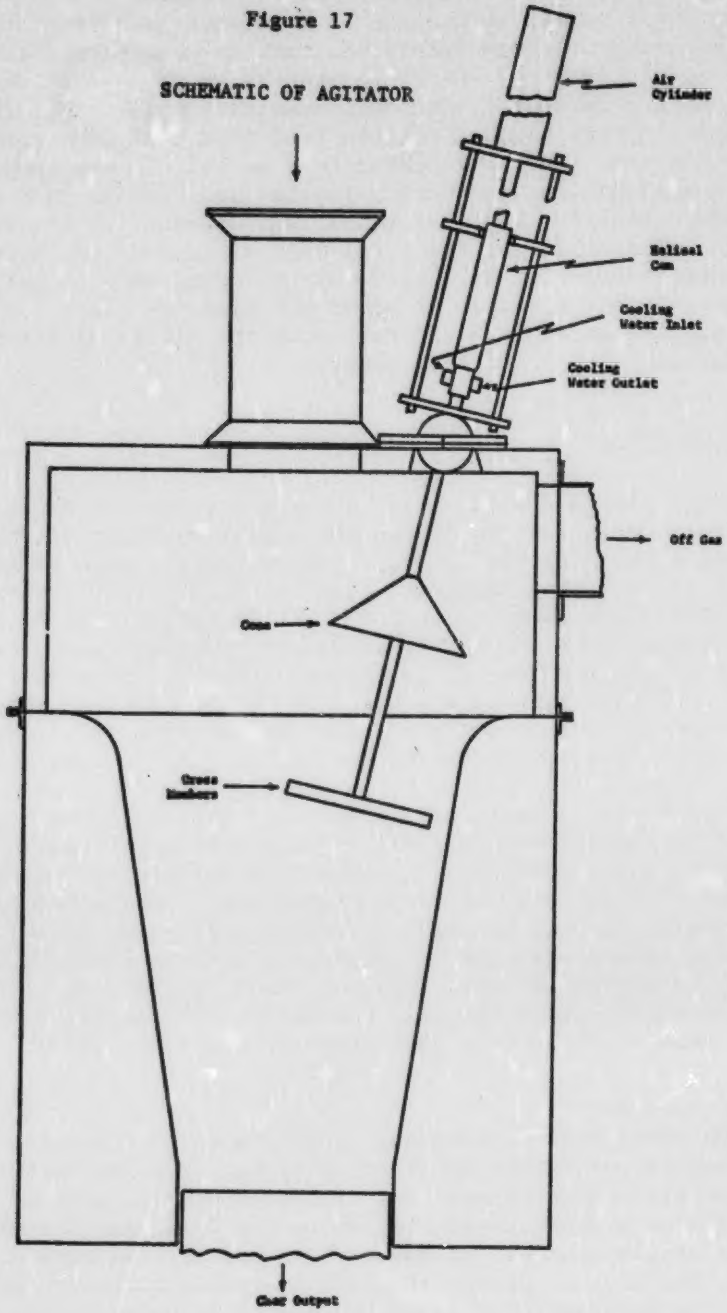
CALIBRATION AND TEST PROCEDURE

Prior to the testing many elements of the system instrumentation were carefully calibrated. The accuracy of some components such as the thermocouples, however, was not checked since the required precision did not demand temperature measurements of greater accuracy than the nominal values of the manufactured wire. Also the accuracy of the cooling water meter was taken at face value from the name-plate data. However, careful attention was given to calibrating the process air orifice and also the off-gas orifice against a known reference laminar flow element. Both these ASME sharp-edged orifices were calibrated in situ to insure accuracy. An input feed rate back-up system, which measured the number of rotations of a screw in the receiving bin, was calibrated directly by weighing a number of drums of feed passing through the bin. (This was later used as a check to be certain that all input drums were recorded properly.) Tares were individually determined for all the drums in which the dried feed was stored.

The procedure during the tests was relatively straightforward: the unit loaded with feed or char the previous day, was heated-up by use of an external gas fired burner. When the temperature was sufficiently elevated, the process air was introduced slowly and the burner turned off. Normally the bed temperature would begin to rise sharply after introduction of the process air; however, if the air was added too soon, erratic operation occurred and it was necessary to turn the gas fired burner on again for additional heat. Once it was apparent that the system was operating in a self-sustaining mode, the output system was activated and slowly brought-up to the operating capacity chosen for the test. Likewise the process air feed rate was adjusted to correspond to the desired ratio of air-to-feed for the test. The system was then allowed to come to a steady-state condition, which required a nominal four hours. Constant checks and adjustments were made during this period to insure that the actual operating conditions were those desired; however, it was found that the

Figure 17

SCHEMATIC OF AGITATOR


Air Cylinder
Helical Cam
Cooling Water Inlet
Cooling Water Outlet
Off Gas
Cone
Cross Members
Char Output

ability to establish a given feed process rate and a given air-to-feed ratio was limited to a tolerance of plus or minus about 10 percent.

Upon initiation of the test run, continuous records of time, feed input, char output, oil output, orifice manometer readings, and the various temperatures were made. In addition a continuous sample of the pyrolysis off-gases was taken. Every effort was made to insure that the unit remained in a steady-state operating mode by continuous surveillance and adjustment of the various instruments measuring and controlling the inputs of the system. "Grab samples" of the feed from each drum were taken throughout the run. Each run lasted four hours. At its completion all of the char and oil produced were collected and representative samples of each were obtained. The char sample was obtained by sequential use of a riffle splitter to cut the total char yield down to, typically, a five pound specimen. The oil which was collected in a 55 gallon drum was mixed thoroughly and a sample of about one pint was taken. All of the feed grab samples were mixed and cut using the riffle splitter to obtain a composite sample of about five pounds.

LABORATORY PROCEDURE

The laboratory played a vital role in the determination of the feed and products characteristics and in the subsequent analysis of the data. Thus the work was checked carefully and every precaution made to insure the accuracy of the results. However, despite these efforts there are occasional instances where inconsistencies did arise. While inherent errors associated with the specific test procedures themselves clearly contributed to the problem, it is believed that the principal explanation for these occasional inconsistancies lies in the difficulty of sampling. Frequently and of necessity a few grams sampled from a run were taken to represent the entire production of the oil or char in some piece of sensitive, chemical analysis laboratory equipment. Thus even though duplicate tests were usually made, there are some occasional problems with repeatibility of results. While inspection of the data reveals that these variations are predominantly less than one percent and that the overwhelming impression is of good repeatability, the presence, especially[+] in the elemental carbon, hydrogen, nitrogen and oxygen (CHNO) analysis, of even small inconsistancies in oxygen content was found to have a significant effect on the test results. Thus, while these data, by ordinary standards, stand up well, the sensitivity of the overall test results to some of these data make close scrutiny necessary.

[+] It might be noted that conventional practice in coal analysis involves obtaining oxygen percentage by difference, once the CHN analysis is complete. This is apparently done because the oxygen percentage must be obtained from analysis of a separate sample, while the C, H, and N analyses are made with a single sample. In the tests reported, the oxygen was measured separately, but because of the sampling difficulties mentioned, there are occasional inconsistencies and caution should be exercised in the casual use of these numbers. Clearly, the calculation of oxygen content by differences is a respectable alternative.

A review of the breadth of the laboratory work done reveals a wide assortment of different analytical procedures. These procedures include analysis of the:

1. Feed for:
    - percent moisture
    - percent ash
    - percent acid-insoluble ash
    - percent carbon
    - percent hydrogen
    - percent nitrogen
    - percent oxygen
    - heating value
2. Char for:
    - percent moisture
    - percent ash
    - percent acid-insoluble ash
    - percent volatiles
    - percent carbon
    - percent hydrogen
    - percent nitrogen
    - percent oxygen
    - heating value
3. Oils for:
    - percent moisture
    - percent carbon
    - percent hydrogen
    - percent nitrogen
    - percent oxygen

The composition of the off-gas was determined by gas chromatography and reported as:

- percent nitrogen
- percent carbon monoxide
- percent carbon dioxide
- percent hydrogen
- percent methane
- percent C_2 components
- percent C_3 components
- percent C_4 components

In addition to the above, analysis of selected samples of feed, char and oil were made to determine the quantities of trace elements such as:

- zinc
- copper
- colbalt
- nickel
- iron
- vanadium
- chromium
- manganuse
- sulfur
- chlorine

The laboratory also provided data regarding the oil viscosity over a range of boiling points. And finally, analysis of the stack gas emissions for a selected test was made. Presented in the following sections are brief descriptions of the laboratory procedures followed to obtain all these data and estimates of the accuracy limits intrinsic to the tests themselves. The data itself is presented in Appendix A.

Solid Samples

Sample Preparation - The solid samples examined consisted of the dried pine sawdust used as feed material for the waste convertor and chars produced by the convertor. The sample size received in the laboratory ranged from one to eight liters for the sawdust feeds and from one to two liters for the char products.

The samples were thoroughly mixed and divided by quartering or by a riffle splitter to produce a representative one liter sample, which was passed through a Wiley Model 4 mill using a six millimeter screen. The ground sample was again mixed and divided into approximately equal parts. One part was again passed through the Model 4 Wiley mill using a two millimeter screen. This material was then mixed and reduced by quartering to approximately 100 grams. The 100 gram sample was then passed through a Wiley intermediate mill using a 40 mesh screen, remixed, and quartered. The larger portion of the -40 mesh sample was stored in a tightly closed glass bottle for use in laboratory analysis. The remaining quarter of the material was again passed through the Wiley Intermediate mill using an 80 mesh screen, remixed, and stored in a tightly capped vial for elemental analysis.

Analytical Procedures - 1. Percent Moisture in Sawdust Feeds: Duplicate 1.000 gram samples were placed in aluminum dishes and dried for one hour at 105°F in a forced air oven. The dried samples were cooled in a desiccator and weighed. The estimated error is ± 0.6 percent (absolute).

2. Percent Moisture and Percent Volatiles in Chars: These analyses were performed by ASTM Method D-271. The estimated error is ± 0.3 percent (absolute).

3. Percent Ash and Percent Acid-Insoluble Ash in Feeds and Chars: Duplicate 1.000 gram samples of the feed or char were weighed into tared

porcelain crucibles, ignited to constant weight in a muffle furnace at 600°C, cooled in a desiccator, and reweighed. The ash was digested in a 1:3 mixture of hydrochloric and nitric acids for 30 minutes. The mixture was then diluted to approximately 100 ml. and filtered through a Whatman No. 40 paper. After thorough washing with distilled water the filter paper and undissolved ash was returned to the crucible used for the original ash determinations, ignited to constant weight at 600°C cooled in a desiccator, and weighed. The estimated error is ± 0.2 percent (absolute).

4. Heating Values: The heating values of the feeds and chars were determined in a Parr Plain (Isothermal Jacket) oxygen bomb calorimeter, following the procedures described in pp. 33-38 of Oxygen Bomb Calorimeter and Combustion Methods, Technical Manual No. 130, Parr Instrument Company, Moline Illinois (1960). Agreement among replicate samples was better than 2.5 percent (absolute) for the feeds and 3.5 percent (absolute) for the chars.

5. Elemental Analysis: Carbon, hydrogen, nitrogen, and oxygen were determined using a Perkin Elmer Model 240 Elemental Analyzer. The manufacturer claims a precision of ± one percent (relative) for pure, crystalline materials. Because of the heterogeneous nature of the samples, and the resulting difficulty of selecting a representative three milligram sample, and due to loss of volatiles from the chars in the purge fraction of the analytical cycle, occasional variations as high as 12 percent (absolute) have been observed in the carbon and oxygen determination on char samples. In most cases, however, the agreement was better than six percent (absolute) for carbon and oxygen in the feeds and chars. Agreement among replicate hydrogen or nitrogen determinations was better than one percent.

6. Trace Metals Analysis: Five gram samples of sawdust feeds and chars were ashed at 600°C and the ash was digested in aqua regia. The mixture was diluted and filtered through glass filter paper, which was then washed with distilled water. The filtrate and washings were combined and diluted to a known volume in a volumetric flask. Trace metals were determined on an Instrument Laboratories Model 251 Atomic Absorption/Flame Emission Spectrophotometer, according to the Instrumentations Laboratories Manual. Copper, chromium, cobalt, iron, manganese, nickel, and zinc were determined by atomic absorption. Vanadium was determined by flame emission. The occasional high level vanadiums were rechecked on separately ashed samples. Since the rises in vanadium levels were accompanied by rises in the levels of iron and manganese it was believed that the relatively high level of metals arose from tool steel introduced during materials preparation or sample grinding.

Oil Samples

Sample Preparation - The oil samples received in the laboratory were stored in tightly closed glass bottles and stirred before each analysis.

Analytical Procedures - Percent Moisture in Oil: The percent moisture in the oil was determined by the method of Dean and Stark. The error is believed to be ± five percent (relative), although the oil is known to begin to decompose partially with liberation of additional water at the temperature of the toluene-water azeotrope, and that acetone and other water soluble compounds have been detected in the head space over stored oil samples.

Non-Condensible Gas Samples

Sample Preparation - Gas samples were drawn continuously from the head space in the waste convertor or from the upstream end of the condensers. The sample stream was passed through a series of water cooled condensers, a glass wool demister, an ice cooled trap, a chemical drying tube, and a dry test meter to a tee in the sampling line. From the tee the major portion of the sample was exhausted to the atmosphere through a vane type pump. A smaller portion of the stream was led from the tee through a tubing pump and a wet test meter into a 96 liter "Saran" gas collection bag. The flow rate in the gas streams was held constant throughout the sampling periods. At the end of the test the waters and oils from the condenser train were measured and the gas collection bag was closed and returned to the laboratory for analysis.

Analysis of Non-Condensible Gas Samples - The gases were mixed by kneading the sample collection bag and their concentrations were determined by gas chromatography. Oxygen and nitrogen were determined using a Perkin Elmer Model 990 Gas Chromatograph using helium carrier gas, a Molecular Sieve 5A column, and a thermal conductivity detector. Hydrogen was determined in a similar manner using argon as the carrier gas. Carbon monoxide, methane, and carbon dioxide were determined in the same instrument using helium carrier gas and an activated carbon column. Hydrocarbons containing two or more carbon atoms were determined in a Perkin Elmer Model 154 instrument using helium carrier gas, a Perkin Elmer "R" column, and a flame ionization detector. The estimated error was ± five percent (relative).

Stack Gas Analysis - Gases were drawn from the exit of the vortex burner through a stainless steel probe then through a "Tygon" connecting tube into a glass gas collection bottle equipped with a rubber septum and glass stopcocks. After thoroughly purging the bottle with stack gases, the bottle was closed and returned to the laboratory for analysis by gas chromatography, as described in the preceding section.

RESULTS OF EXPERIMENTAL PROGRAM

General

The importance to the conduct of the tests of rapid-feed-back of the laboratory results was one of the major lessons learned from the test program. Without the rapid turn-around of the data, the testing would have been practically conducted in an information vacuum. Thus it was essential that the overall test results be computed as they were generated to maximize the useful information from the experimental work. Hence while in this study it was not always possible to get written laboratory results in the time desired, continuous verbal communication with the laboratory personnel provided sufficient information to adequately guide the testing.

In the testing, a total of 19 runs were made, however the data for only 14 are presented in detail here. These are runs 4, 5, 6, 7, 8, 9, 10, 12, 13, 15, 16, 17, 18, and 19. The detailed results from runs 1, 2, 3, 11, and 14 are not reported for the following reasons:

- Run 1 was basically a shakedown to check out newly installed instrumentation and modified test procedures.
- Run 2 was only a preliminary test and conducted to determine the difference in the char and oil yields between operation with feeds of pure sawdust and a fifty-fifty mixture of sawdust and pulverized bark. In the run, separate two hour tests were made at a constant feed rate and air/feed ratio. Table 2 presents the test conditions and the results of this run. From this table it appears that the yields are essentially equivalent and for this reason and because a local convenient supply of pulverized bark was not available, all further testing was conducted using sawdust alone.
- Run 3 was aborted because of a small leak in one of the cooling water lines.
- Run 11 was an attempt to duplicate run 7 but because of an inability to establish close enough correspondence to the desired test conditions, it was terminated.
- Run 14 was an attempt to test at low air/feed and at a very low feed rate. The test was terminated because the unit operation became unstable and the output became intermittant.

One of the parameters to be investigated in the test program was that of mechanical agitation. The use of agitation has as its objective the increase in process rate and the prevention of blockages-to-flow which sometimes can occur with bulky feeds. To evaluate the effects of agitation on yield, a comparison should be made of the effects on maximum throughput with and without agitation. This was tried but it was found that at a certain process rate without agitation the operating pressure rose to near the maximum allowable. There is little doubt that had the maximum allowable unit pressure been higher, then greater process rates would have been possible without the need for agitation. Clearly with agitation the process rate and pressure would have increased even further. Thus the limitations of the unit operating pressure prevented the evaluation of the effects of agitation on maximum process rate.

TABLE 2

SUMMARY OF RESULTS OF RUN 2

	Sawdust	Sawdust/Bark
Feed Rate (pound/hour)	368	385
Air/Feed (pound/pound)	0.36	0.35
Char (pound)	143	166
Char Yield (percent)	19.4	22.5
"Oil" (pound)	92	93
"Oil" Yield (percent)	12.5	12.1

Only the influence on product yields could be tested. Had the unit been drafted, rather than pressurized, then the draft fan might have been operated at a higher rpm and the problem avoided. However with sawdust, which is a relatively free-flowing material with a small angle of repose, it might be expected that the influence of agitation on process rate would not be strong in any case and therefore the effects on maximum process rate would likely be unimportant.

Thus while the original objective to evaluate the effects of agitation could not be completely met, the other test parameters were studied with no difficulty and the conduct of the tests, as subsequently described, was relatively straightforward.

Presented in Table 3 is a summary of the test conditions for the 14 reported runs. The table shows the values of bed depth, air/feed ratio, feed rate and the number of air tubes utilized. Also indicated is whether or not the mechanical agitator was operated and also the air tube configuration investigated. Clearly there are a large number of tests that could be conducted with even two values of each of these parameters. With a program of only 14 tests, some discretion had to be applied in selection of the test conditions. Therefore the choice of the parameters used in the tests was substantially influenced by experience from previous tests and when a parameter was seen to have little effect on the results, further investigation of its influence was abandoned.

In considering the test parameters, it was anticipated at the outset that the most desirable results were to be obtained at low air/feed ratios (since this corresponds to low temperatures) and at maximum bed depth. Therefore the amount of testing at the greatest depth given equalled all that at the two lower levels combined, with the minimum depth given least. It was also anticipated that with sawdust the effects of agitation would be unimportant on yields; therefore these tests were performed early in the program, verifying the expected results. Likewise the effects of air tube geometry and the number of air tubes was not expected to be significant, so only a few tests at an intermediate bed depth where the tube geometry could be varied easily were made.

Therefore in the test program emphasis was placed on the effects of air/feed ratio and feed rate on the product yields at a maximum bed depth. In the tests at maximum bed depth the practical operating limits of the unit at minimum and maximum process rates and at minimum air/feed ratios were also investigated. Because these limits were reached in runs 6 and 13 and because the existence of these limits influenced the oil yields, especially, care must be exercised interpreting the results from these two runs. Otherwise the data from the runs at the greatest bed depth appear consistent with the general trends of the overall test results.

TABLE 3

Operating Conditions

Run Number	Bed Depth (in.)	Agitation	Number Air Tubes	Air Tube* Configuration	Air/Feed (lb/lb)	Feed/Rate (lb/hr)
4	18	no	4	A	.47	291
5	18	yes	4	A	.53	246
9	27	no	3	B	.70	184
10	27	yes	3	B	.64	184
17	27	no	3	B	.38	195
18	27	no	2	C	.58	189
19	27	no	2	C	.42	186
6	39	no	2	D	.27	491
7	39	yes	2	D	.56	202
8	39	no	2	D	.35	226
12	39	no	2	D	.45	237
13	39	no	2	D	.38	118
15	39	no	2	D	.22	346
16	39	no	2	D	.49	222

* Configuration A involved four tubes, 2 at a depth of 16 inches, and two at a depth of 20 inches.

Configuration B involved 3 tubes at a depth of 27 inches.

Configuration C involved 2 tubes at a depth of 27 inches.

Configuration D involved 2 tubes at a depth of 39 inches.

Data Analysis

Before discussing the results of the runs specifically, the procedure used to analyze the raw data should be described. The raw data comprised the basic information concerning feeds, temperatures, product yields, etc. from the tests; but the feed, the oil and the off-gases contained water, for example, which had to be accounted for. Therefore, the laboratory analysis of these samples was used to correct the data to a dry basis. Hence for this reason and for others there was a continuous interplay in the data reduction between the laboratory results and the basic test results. Moreover, in the reduction of the data and the computation of the mass and energy balances, additional chemical balances were made to complement and correct the basic relationships. The following is offered to illustrate why this was necessary:

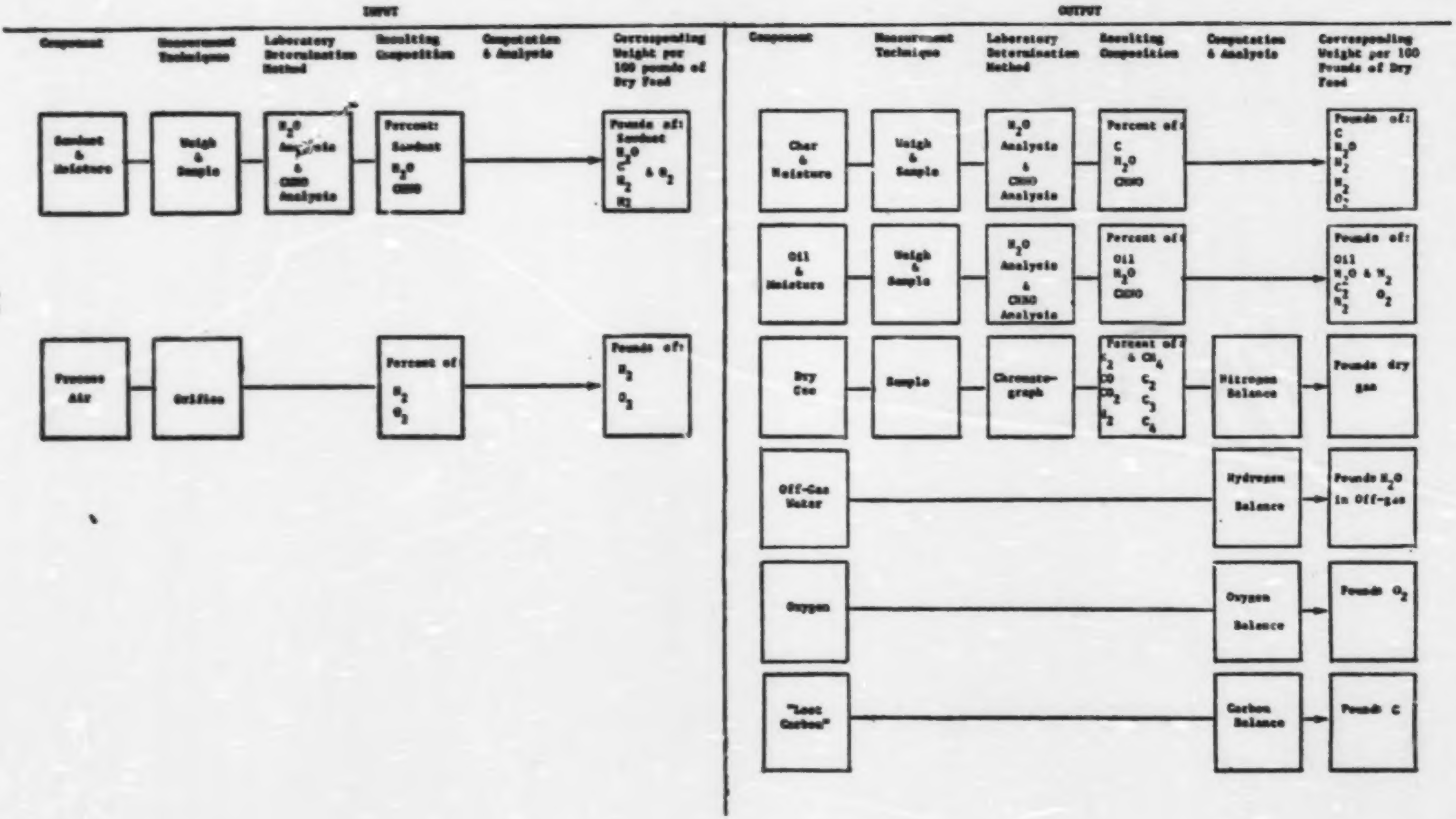
> Throughout the test program it was observed on numerous occasions that oil was collecting in and dripping from a flange upstream of the burner but downstream of the condenser and the off-gas flow orifice. This oil was apparently passing through the orifice in the form of droplets and had its origin in the condenser where it was picked up by the off-gas stream. Several efforts to prevent this from occurring proved futile and it was finally concluded that the design of the condenser itself was primarily the cause. Because of this occurrence the basic orifice measurements were considered suspect and, the use of a nitrogen balance was employed to determine the off-gas flows. Moreover because of the loss of oils, the resulting oil yields were significantly lower than anticipated from the laboratory results but again a back-up technique, a carbon balance, allowed an estimate of the amounts lost to be made. In terms of the total feed flow rate, the amount of oil passing through the orifice did not represent a significant mass loss, however in terms of the energy flow, it represented a substantial proportion and corrections were necessary to obtain an adequate energy balance.

Thus in the mass and energy balances, a number of additional chemical balances and checks were made. To illustrate this procedure, the complete data reduction process for the various chemical and mass balances is presented schematically in Figure 18. Study of the figure indicates that it is divided into two sections, e.g., Inputs and Outputs. Concerning Inputs, the figure shows that the feed was analyzed for its water content, and C, H, N and O analyses were performed. This then allowed computation of the amounts of dry feed processed and the corresponding amounts of water, carbon, hydrogen, nitrogen, and oxygen. The process air flow rate and the chemical composition of atmospheric air allowed calculation of the amounts of nitrogen and oxygen utilized.

The output char contained a small volatile or moisture content and this was determined in the laboratory along with the elemental composition which was found by use of a CHNO analysis. These procedures allowed

Figure 10

Mass and Chemical Balance Calculation Procedure


INPUT
Component
Measurement Technique
Laboratory Determination Method
Resulting Composition
Computation & Analysis
Corresponding Weight per 100 pounds of Dry Feed
Sawdust & Moisture
Weigh & Sample
H_2O Analysis & CHNO Analysis
Percent: Sawdust H_2O CHNO
Pounds of: Sawdust H_2O C & O_2 H_2 N_2
Process Air
Orifice
Percent of: N_2 O_2
Pounds of: N_2 O_2
OUTPUT
Component
Measurement Technique
Laboratory Determination Method
Resulting Composition
Computation & Analysis
Corresponding Weight per 100 Pounds of Dry Feed
Char & Moisture
Weigh & Sample
H_2O Analysis & CHNO Analysis
Percent of: C H_2O CHNO
Pounds of: C H_2O H_2 N_2 O_2
Oil & Moisture
Weigh & Sample
H_2O Analysis & CHNO Analysis
Percent of: Oil H_2O CHNO
Pounds of: Oil H_2O & N_2 C_2 O_2 H_2
Dry Gas
Sample
Chromatograph
Percent of: N_2 & CH_4 CO C_2 CO_2 C_3 H_2 C_4
Nitrogen Balance
Pounds dry gas
Off-Gas Water
Hydrogen Balance
Pounds H_2O in Off-gas
Oxygen
Oxygen Balance
Pounds O_2
"Lost Carbon"
Carbon Balance
Pounds C

determination of the weight of carbon, water, hydrogen, nitrogen and oxygen in the char for each run. Similar procedures allowed computation of the amounts of water, carbon, hydrogen, nitrogen, and oxygen in the condensed oil.

The dry non-condensible gas composition was obtained from gas chromatographic determinations. Using the percent nitrogen found in the off-gas and the total nitrogen input from the process air the amount of dry pyrolysis gas was calculated. Investigations indicated that the nitrogen in the feed, the char and the oil is small and can be ignored when performing elemental mass balances.

The water content of the off-gas was obtained from a hydrogen balance. In this calculation the difference between the sum of the input hydrogen from the sawdust and associated moisture and the sum of the hydrogen in the output char, oil and dry gas, (including the char and oil moisture) was determined. Then this hydrogen was assumed to be associated with a corresponding quantity of water and this value taken as the water content of the off-gases. As a check on this procedure an oxygen balance was made using that oxygen associated with the measured input feed and process air, the measured char, oil and gas outputs and that calculated for the water. The difference between the input oxygen and the output oxygen was found to be never more than a few percent with an average for all 14 runs of only 0.8 percent. This then confirmed the assumptions inherent in the hydrogen balance and gave confidence to the overall mass balance procedures.

Upon summing up the weights of the carbon, oil, water, and dry gas in a mass balance it was typically found that seven to 10 percent of the output products were unaccounted for. Because of the confidence held in the char measurements and the computed values of water and dry gas it was felt that this lost material most likely was oil. While this loss did not appreciably affect the mass balance it had a major impact on the energy balance. This led to an additional computation, a carbon balance to determine the "lost carbon."[‡] From the carbon balance it was found that the amount of carbon missing from the products was on the average very near that missing from the calculated mass balance; thus the surmise that the "lost carbon" and the lost oil were the same was substantially strengthened. This then was taken as fact in further analyses and the mass and heat balances calculated with the computed values of "lost carbon." Presented in Appendix B is a sample calculation for the results of run 7 illustrating the preceding discussion.

[‡] Since the carbon content of the dry pyrolysis oil is so large, it can be considered for practical purposes as "liquid carbon." It was known from the testing that considerable quantities of the oil were unaccounted for and that the yields were well below those expected from the laboratory results; therefore the suspicion that the lost carbon and the lost oil were essentially the same was based on substantial but indirect evidence.

Discussion of Results

The results of the experimental work are shown in Tables 4 and 5. A summary of the most important data upon which the conclusions from this investigation are derived is presented in Table 6. Study of the results from run 4 and 5, 9 and 10, 7 and 16, shows conclusively that the effects of agitation on product yields are unimportant.**

Comparison of the data from runs 10 and 18 indicate that tube geometry probably has little effect on product yields, although a comprehensive study of this parameter was not made.

From a study of the data from all the tests it appears that the effect of bed depth on char yields is unimportant; however the deeper beds may result in greater oil yields and therefore may be more desirable in maximizing the production of the char-oil mixture.

The most dramatic effect and the one which overrides the importance of any of the other test parameters is the air/feed ratio. This is illustrated in Figure 19 which shows a plot of char yields as a function of air/feed and Figure 20 which presents a graph of the percent of the available energy in the char-oil mixture as a function of air/feed. These figures are plots of all the test data at various bed depths, tube geometries, feed rates, and with or without agitation. Clearly the air/feed ratio is the dominant parameter and small values are the most desirable.

It is interesting to note in Figure 20 the value of the available energy fraction extrapolated to zero air/feed. This value is nearly identical with that obtained from the tube furnace tests at a minimum pyrolysis temperature and shown in Figure 9. Since the pilot plant operating conditions and those of the tube furnace become more nearly comparable at zero air/feed this result strengthens the test findings and provides a possible means of correlating the laboratory and the pilot plant test data.

Presented in Figure 21 is an energy breakdown of the pyrolytic products, including losses, as a function of air/feed. The data are plotted using the results shown in Table 5 and no consideration is given to the various values of bed depth, tube geometry, etc. The graph reinforces the earlier results which indicate the primary influence of the air/feed ratio on product yields. The figure graphically illustrates how the various energy forms change with increasing air/feed and also demonstrates the generally good closure of the energy balance.

**It is important to note that mechanical agitation has been shown in previous studies with bulky wastes to have a pronounced effect on the outcome of the testing. Thus the fact that in these tests with this feed and this agitator the effects were unimportant should not be generalized to less free-flowing solids.

TABLE 4

OVERALL MASS BALANCE*

	OUTPUT						INPUT					OXYGEN BALANCE			CARBON BALANCE		
Run Number	Char Yield (lb)	Oil Yield (lb)	Off-Gas Yield (lb)	Char & Oil (lb)	Water (lb)	Total Output (lb)	Feed (lb)	Air (lb)	Water (lb)	Total Input (lb)	Difference (lb)	Input (lb)	Output (lb)	Difference (lb)	Input (lb)	Output (lb)	Differene (lb)
4	18.7	6.3	70.4	25.0	45.4	141	100	47.4	7.8	155	14	58.7	61.8	-3.1	45.7	28.7	17.0
5	20.7	6.7	84.2	27.4	42.4	154	100	53.1	8.3	161	7	59.6	63.0	-3.4	45.6	35.0	10.6
9	11.6	14.4	110	26.0	27.1	160	100	70.4	6.4	177	17	63.8	59.0	-4.8	45.6	38.4	7.2
10	10.4	11.3	92.0	21.7	40.3	152	100	63.8	6.4	170	18	60.5	59.1	-1.4	47.1	33.5	13.6
17	28.1	8.1	60.2	36.2	30.0	126	100	38.2	3.9	142	16	54.5	52.1	2.4	48.2	35.3	12.9
18	10.2	11.3	89.0	21.5	39.9	151	100	58.0	6.1	164	13	58.8	58.8	0	47.5	35.2	12.3
19	27.8	14.3	61.6	42.1	32.7	136	100	41.6	7.9	150	14	56.9	46.3	10.6	45.8	45.0	.8
6	25.8	7.8	57.2	33.6	39.4	130	100	27.2	5.8	133	3	54.2	58.8	-4.6	45.3	37.9	7.4
7	16.1	10.1	102	26.2	28.8	157	100	55.8	5.8	162	5	60.5	59.4	7.1	48.2	46.1	2.1
8	22.5	12.0	53.6	34.5	41.5	130	100	34.9	6.8	141	16	55.5	53.1	2.4	46.3	37.9	8.4
12	26.3	5.9	82.9	32.2	39.9	155	100	45.3	6.6	152	-3	57.3	65.0	-7.7	46.5	40.8	4.3
13	28.9	15.0	61.5	43.9	32.9	138	100	37.8	7.3	145	7	55.8	51.2	4.6	46.3	44.6	1.7
15	32.7	12.1	40.5	44.5	32.4	117	100	22.0	3.6	126	9	50.4	48.4	2.0	48.4	42.5	5.9
16	17.4	13.8	78.9	31.2	33.0	143	100	49.2	4.7	154	11	52.5	55.6	-3.1	46.5	38.7	7.8
Average						142				152	10	56.8	56.3	.4	46.5	38.4	8.1
*																	

*All results are presented on a basis of 100 lb dry sawdust.

TABLE 5

OVERALL ENERGY BALANCE *

	OUTPUT[1]											INPUT[1]				
	Chemical Energy				Latent & Sensible Energy											
Run Number	Char	Oil	Off-Gas	"Lost" Carbon	Water Vapor	Off-Gas	Char	Oil	Cooling Water	Con-vective Losses	Total Output	Feed	DIF-FERENCE	RATIO HEAT OUT/HEAT IN		Product Heating Value Char plus Oil (BTU/lb)
4	221	72.7	159	247	51.8	3.2	5.3	1.3	18.7	6.7	787	831	44	.947		12,873
5	214	106	191	154	50.2	4.2	3.0	1.3	17.3	6.5	747	814	67	.918		12,473
9	147	226	259	104	31.3	5.7	3.3	2.9	22.0	6.5	807	811	4	.995		14,367
10	131	181	197	197	46.4	4.4	2.1	2.3	26.6	6.6	794	820	26	.968		14,419
17	284	132	118	187	34.3	2.4	7.3	1.6	20.3	6.7	794	832	38	.936		12,231
18	133	172	221	178	47.1	5.6	2.7	2.3	14.0	6.6	782	827	45	.946		14,289
19	304	229	146	11.6	38.7	4.3	8.3	2.9	16.6	6.7	768	832	64	.923		12,694
6	338	106	166	107	45.0	2.6	7.4	1.6	5.6	6.5	786	814	28	.966		13,439
7	216	172	288	30.5	32.9	4.7	5.0	2.1	20.0	6.5	778	814	36	.955		14,788
8	295	198	117	122	47.4	2.5	6.6	2.4	15.7	6.6	797	823	26	.968		14,335
12	334	97.4	167	62.4	46.8	5.6	7.0	1.2	13.0	6.6	742	820	78	.905		13,528
13	336	252	126	24.7	37.0	2.0	7.4	3.0	15.3	6.5	810	818	8	.990		12,711
15	363	197	122	85.6	37.1	1.8	8.5	2.4	5.5	6.6	828	825	-3	1.004		12,733
16	235	203	200	113	38.4	4.6	6.5	2.8	12.8	6.7	823	842	19	.977		14,128
Average											789	823	34	.959		

*All results are presented on a basis of 100 lb dry sawdust.

[1] In thousands of Btu's.

TABLE 6

SUMMARY OF TEST RESULTS

Run Number	Bed Depth (in.)	Agitation	Number Air Tubes	Air/Feed (lb/lb)	Feed Rate (lb/hr)	Char* Yield (lb)	Oil* Yield (lb)	Lost* Carbon (lb)	Mass: Output/Input	Energy: Output/Input	Available** Energy (Percent)	Comments
4	18	no	4	.474	291	18.7	6.3	17	1.02	.947	65.1	
5	18	yes	4	.531	246	20.7	6.7	10.6	1.02	.918	58.2	
9	27	no	3	.704	184	11.6	14.4	7.2	.94	.995	58.8	
10	27	yes	3	.638	184	10.4	11.3	13.6	.977	.968	62.1	
17	27	no	3	.382	195	28.1	8.1	12.9	.98	.936	72.5	
18	27	no	2	.580	189	10.2	11.3	12.3	.99	.946	58.4	
19	27	no	2	.416	186	27.8	14.3	.8	.91	.923	65.6	The oxygen balance was not good.
6	39	no	2	.272	491	25.8	7.8	7.4	1.03	.966	67.7	Due to the high process rate there was a significant loss of oil from the condenser.
7	39	yes	2	.558	202	16.1	10.7	2.1	.95	.939	50.6	
8	39	no	2	.349	226	22.5	12.0	8.4	.98	.968	74.7	
12	39	no	2	.453	237	26.3	5.9	4.3	1.05	.905	60.1	The oxygen balance was not good.
13	39	no	2	.378	118	28.9	15.0	1.7	.96	.990	74.9	At this low throughput, there was a significant amount of oil condensing in the unit with resulting eratic flow.
15	39	no	2	.220	346	32.4	12.1	5.9	.975	1.004	78.3	
16	39	no	2	.492	222	17.4	13.8	8.0	.98	.977	65.4	

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*All results are presented on a basis of 100 lb dry sawdust.

**Energy available in char/oil divided by total available from sawdust feed.

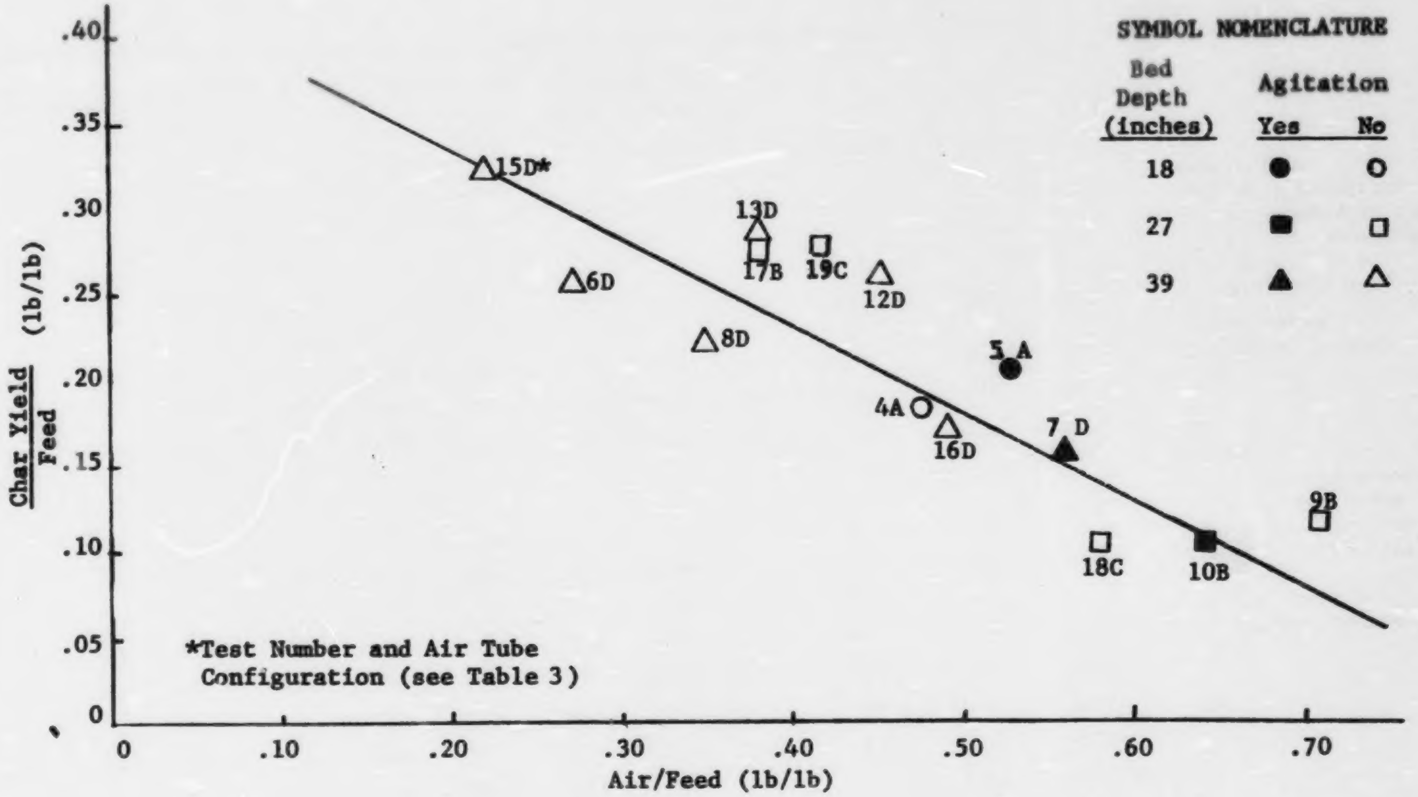

Figure 19

Fractional Char Yields Versus Air/Feed Ratio

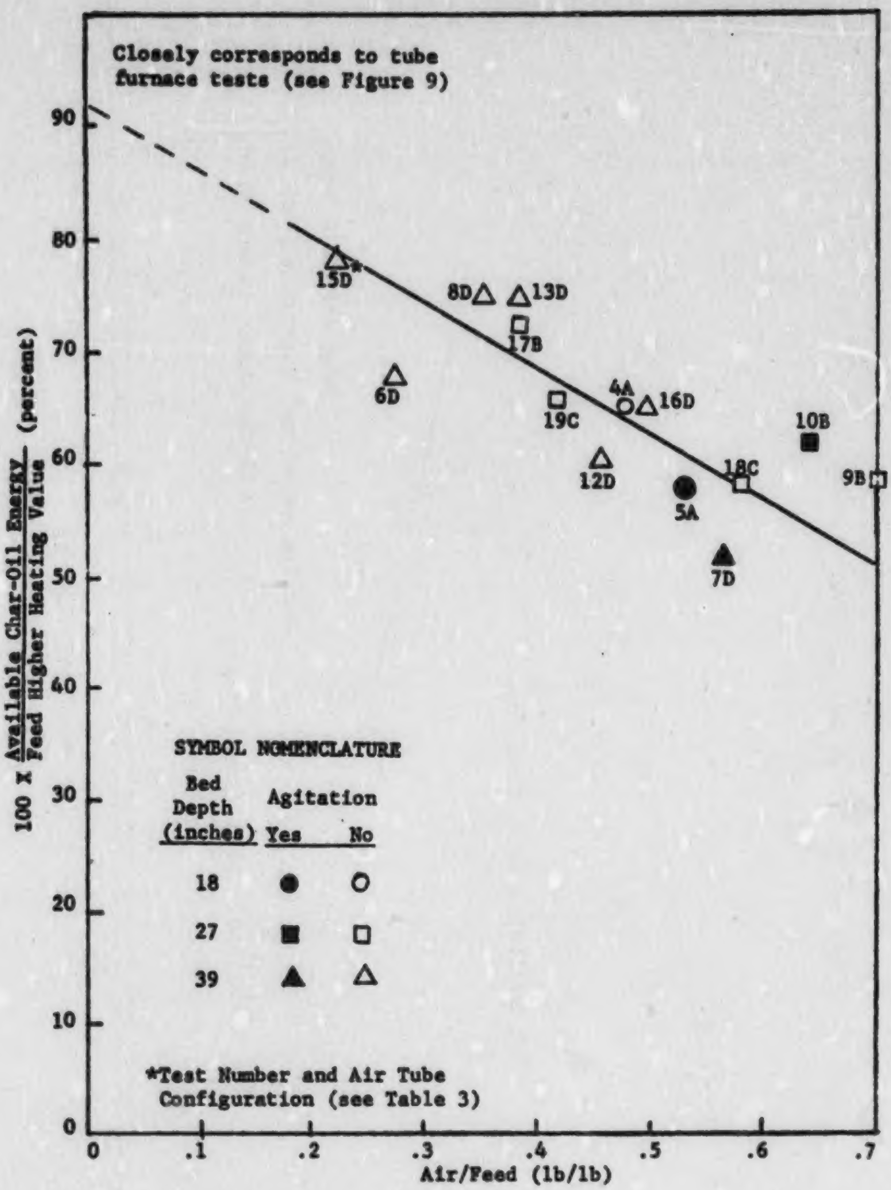

Figure 20

Percent Available

Energy in Char-Oil Mixture

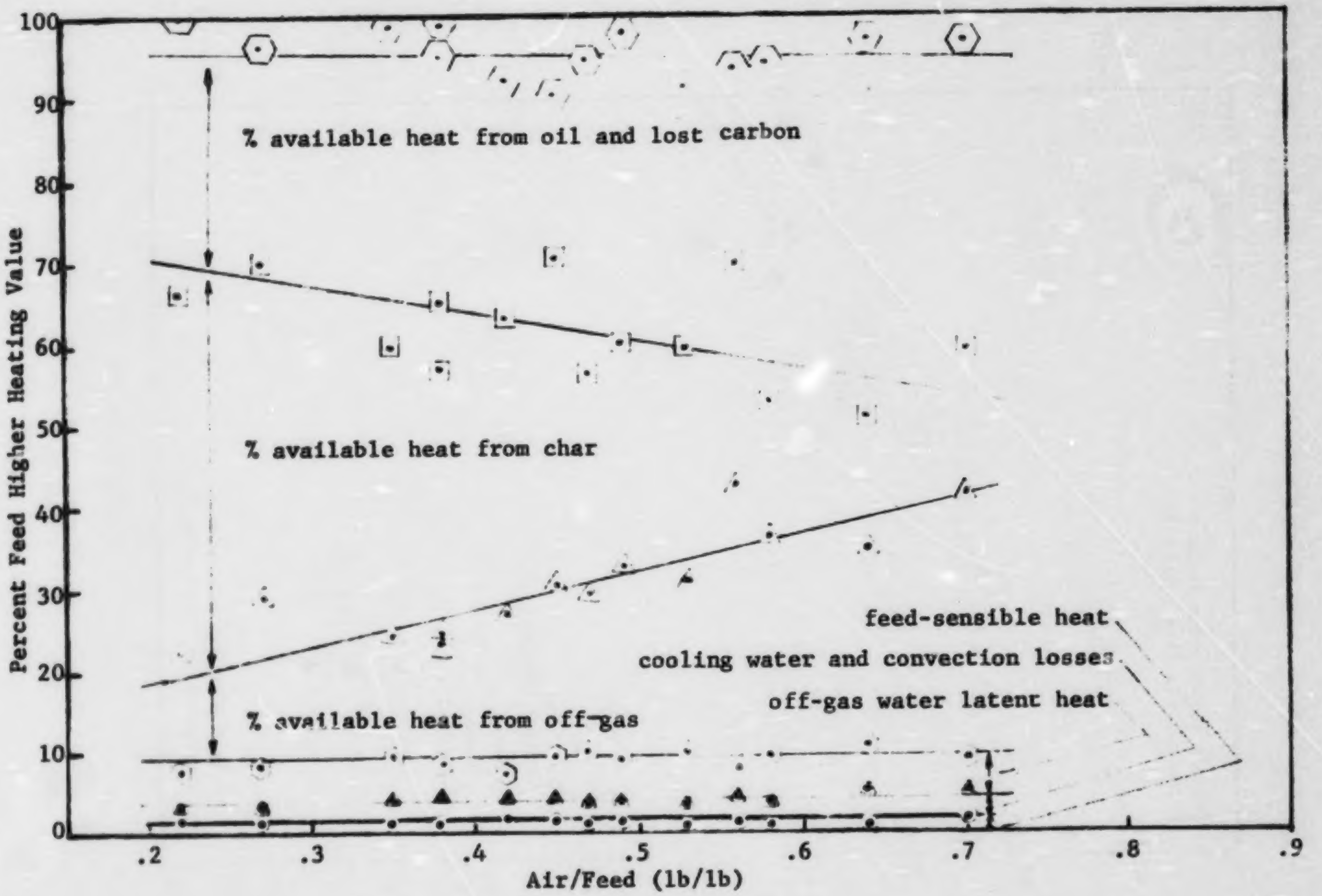

Figure 21

Energy Breakdown of Pyrolysis Products

Figure 22 shows a plot of the non-condensible gas heating value as a function of air/feed. The scatter in the data is greater than experienced elsewhere but there is a definite trend toward a reduced heating value as the air/feed increases. Check of the nitrogen content of the gas shows a corresponding increased percentage which helps explain the lower heating values. Thus while the total heat available from the gas per pound of dry feed increases with increasing air/feed, the heat content of the gas is diminished.

Figure 23 presents a combination of data from Table 5 together with computed heat energy requirements for processing and drying the feed. The computed curve is based on an assumed 1500 Btu required to evaporate each pound of water in the feed and 360 Btu/lb dry feed of raw heat energy required to process the dry feed. This latter figure arises from an assumed 50% derating of the engine power plant for the portable unit, a requirement for 170 hp (see Table 7) and an assumed thermal efficiency of 15 percent. Since the energy required to dry and process the feed must be supplied by the non-condensed gas, the figure provides a means of determining the required air/feed ratio and the available energy in the char-oil mixture for a given feed percent moisture*. To illustrate, at a 50 percent moisture composition, 1860 Btu/lb dry feed would be required for drying and processing. At an air/feed ratio of approximately .47, the available energy in the non-condensible gas would meet these energy requirements and at this same air/feed value the heat available in the char-oil mixture would be approximatley 5500 Btu/lb dry feed with an overall conversion efficiency of about 65 percent.

Clearly as the feed moisture percent becomes much greater than 50 percent the energy available in the char-oil mixture drops off sharply.

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*Moisture composition is defined as pounds of water per pound of mixed feed.

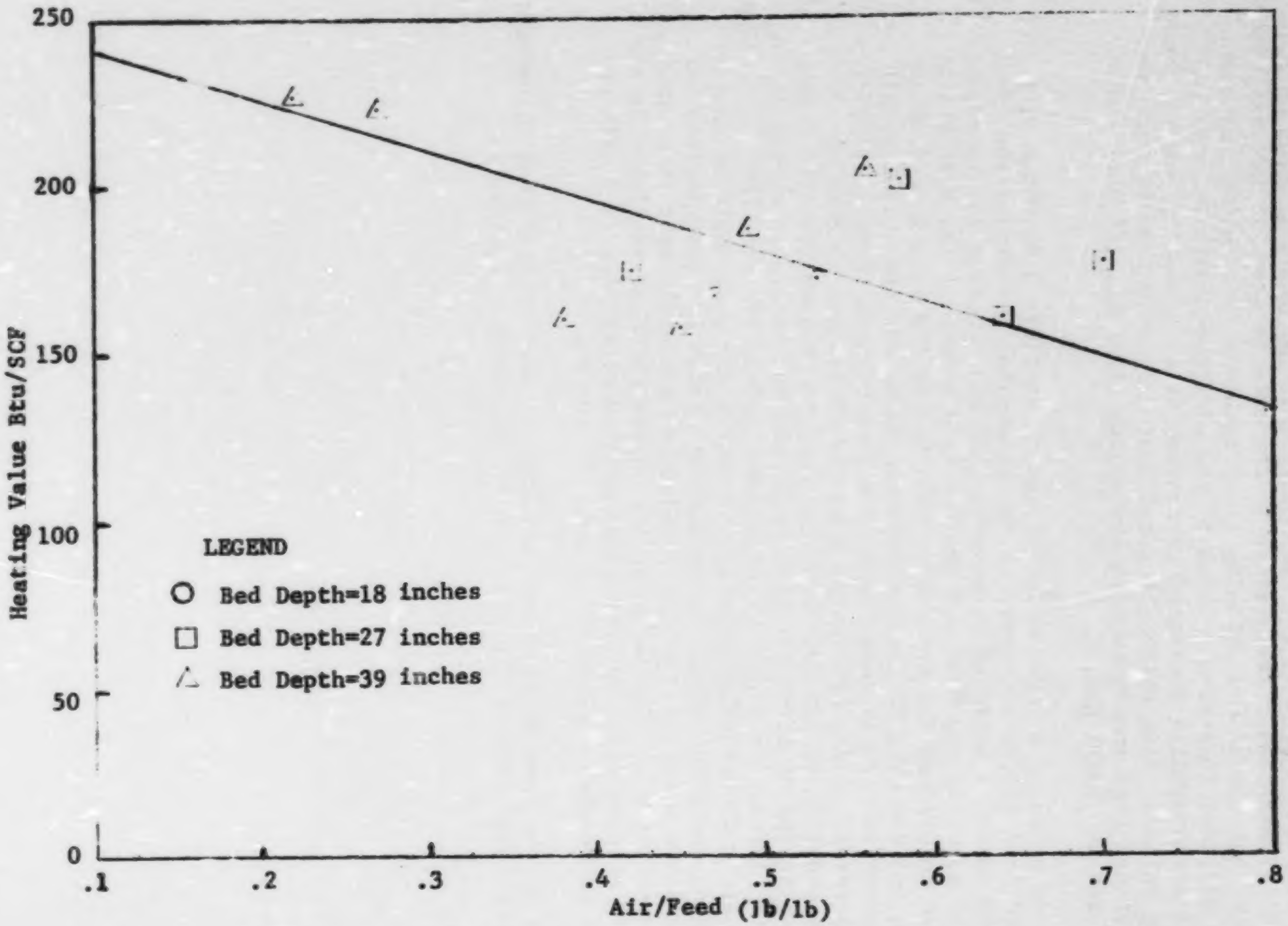
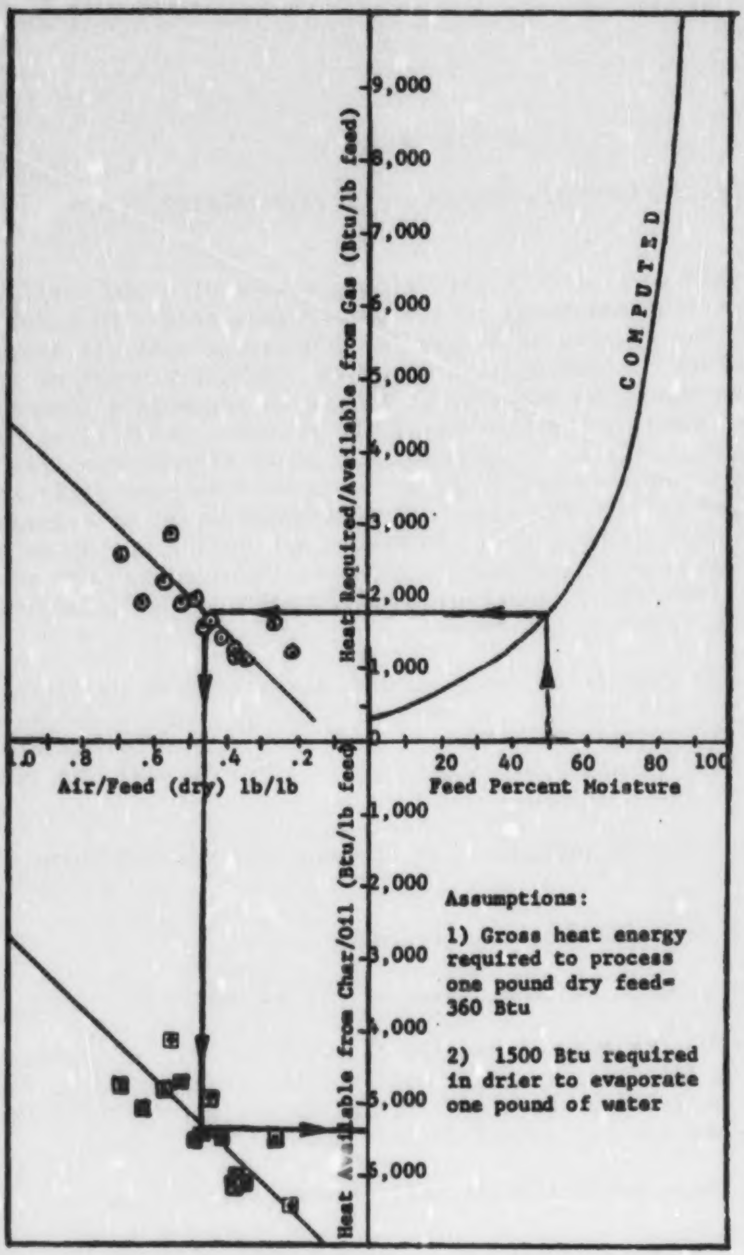


Figure 22

Heating Value of Non-Condensible Gas



Assumptions:

1) Gross heat energy required to process one pound dry feed= 360 Btu

2) 1500 Btu required in drier to evaporate one pound of water

Figure 23

Effects of Feed Moisture on Available Energy from Char-Oil Mixture

SECTION VI

MOBILE PYROLYSIS SYSTEM PRELIMINARY DESIGN

Presented in this section is a preliminary design of a 200 ton/day (assuming 50 percent moisture) mobile pyrolysis system. In addition to the design, the results of a simplified economic analysis are also shown. But before discussing this work, the overall concept of the portable system should be described. Figure 24 presents a schematic view of the proposed manner of operation of the system. As pictured, several mobile units would operate in zones with a large thermal conversion plant at their center. The several units would convert various agricultural and forestry wastes into the char-oil fuel which would be transported to the thermal conversion plant. By proper scheduling and by using the constantly produced wood wastes as a means of leveling out the seasonal fluctuations in the agricultural waste production, a fairly constant supply of wastes could be provided.

As conceived, one char truck could service three or four pyrolysis units and likewise only one tractor for perhaps seven or eight complete systems would be required to move them from site to site. The char trucks would have a closed trailer which would also serve as a char-oil storage container and be exchanged twice daily.

The portable system was designed with certain basic ground rules which are listed below:

- It must be completely self-sustaining
- It must produce no land, water or air pollution
- It must be transported readily and with no special highway permits, i.e., its length should not be greater than 55 feet, its width is eight feet, its height is not more than 13 feet six inches and its weight is less than 73,000 pounds.

In addition to these basic limitations, it was assumed that:

- System does not require any outside source of water for cooling
- The system would comprise two trailers

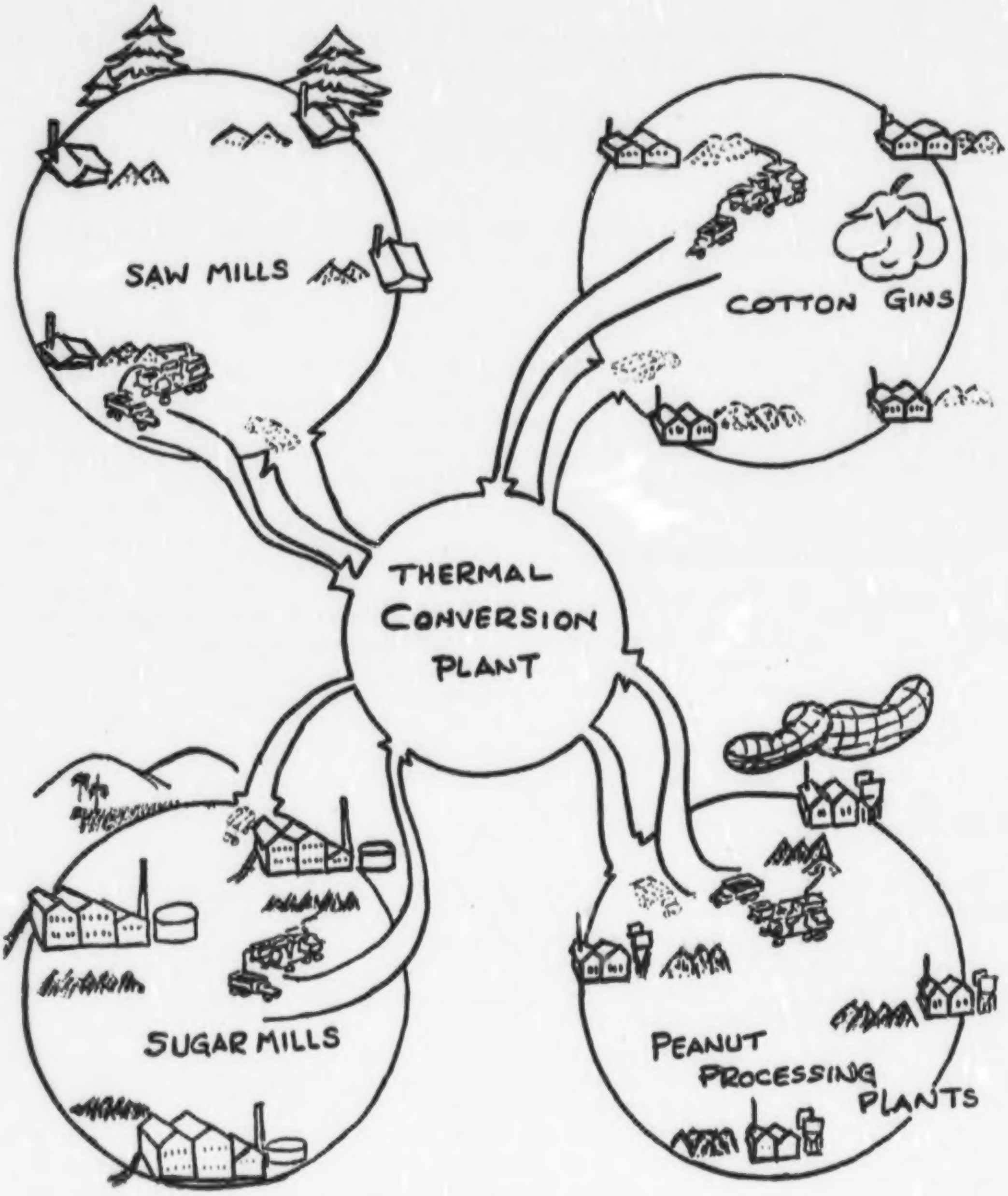

SAW MILLS
COTTON GINS
THERMAL CONVERSION PLANT
SUGAR MILLS
PEANUT PROCESSING PLANTS

Figure 24

Mobile Pyrolysis System Concept

- The start-up would be accomplished using propane

- The oil condenser would operate at a temperature greater than the off-gas dew point to avoid moisture condensation

- A 50 percent derated gasoline engine operating on the low Btu pyrolysis gas would provide the power required to operate the system

- The design rated capacity of the system would be based upon the experience gained with the Cordele, Georgia, demonstration unit.

- The feed, and the resulting char, because of its typically low thermal conductivity, would serve as an insulator on the sides of the unit. This would prevent not only the necessity for and associated weight of a ceramic insulator but also avoid the problems of transporting such a brittle, fragile system

SYSTEM DESCRIPTION AND DRAWINGS

The overall portable pyrolysis system is shown schematically in Figure 25. Examination of the figure indicates that after leaving the hammer mill, the pulverized wet bark, together with the sawdust enters the drier and from there the mixture is conveyed to the waste convertor unit. The char produced is emptied into a mixer where it is combined with the pyrolysis oil. The gases produced in the convertor pass through the cyclone and into the condenser where the higher boiling point oils are removed and mixed with the char. The noncondensed gas then is used to operate the engine generator system and also to supply heat to the drier.

Presented in Figure 26 and 27 are preliminary design drawings of the two trailers which make-up the system. The dominant feature in Figure 26 is the drier. The location and geometry of this unit largely governs the design of the elements on this trailer and significantly influences the overall system layout. Likewise in Figure 27 the major component is the waste convertor, but interestingly the location of this unit has less effect on the overall design than the drier. The drawings show the trailers in their stowed configurations to illustrate that adequate space is available for all the required components. Deployment of the system would mainly involve moving the conveyors from their stowed to their operational locations, connecting up the flexible pipe between the off-gas system and the drier, and unloading the feed hopper by use of a collapsible ramp stowed underneath.

In the operational mode, the trailers would be located adjacent to one another as shown in Figure 28, which presents a plan view of the deployed system. Expanded metal platforms, not shown in Figures 26 and 27 would be folded out from the trailer sides to provide a work space for the operating crew.

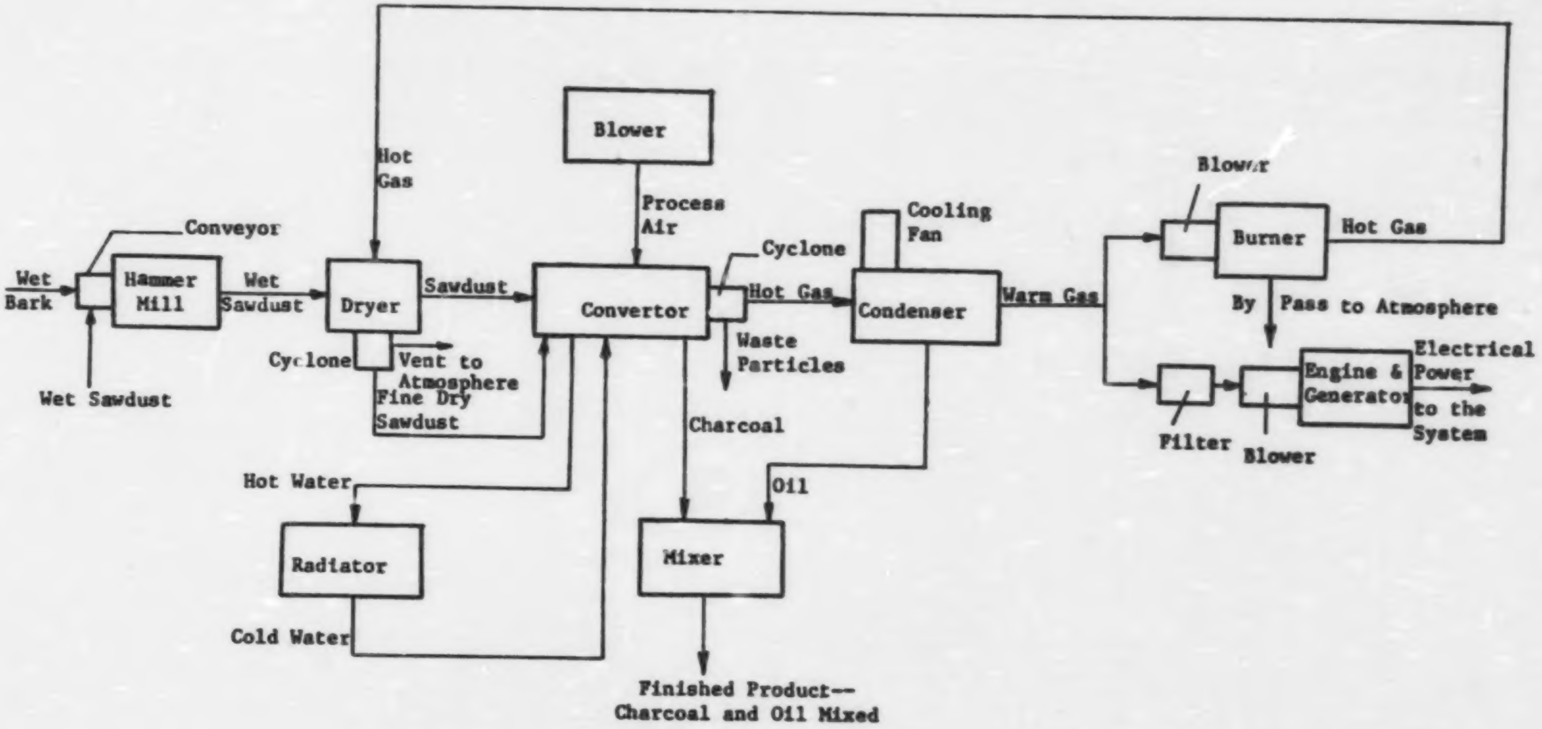

Wet Bark
Conveyor
Hammer Mill
Wet Sawdust
Wet Sawdust
Hot Gas
Dryer
Cyclone
Vent to Atmosphere
Fine Dry Sawdust
Sawdust
Blower
Process Air
Convertor
Cyclone
Hot Gas
Waste Particles
Charcoal
Hot Water
Radiator
Cold Water
Mixer
Cooling Fan
Condenser
Oil
Finished Product--
Charcoal and Oil Mixed
Warm Gas
Blower
Burner
Hot Gas
By Pass to Atmosphere
Filter
Blower
Engine & Generator
Electrical Power to the System

Figure 25

Mobile Pyrolysis Unit Preliminary

Process Flow Diagram

Figure 26

Plan and Elevation Views of Trailer I

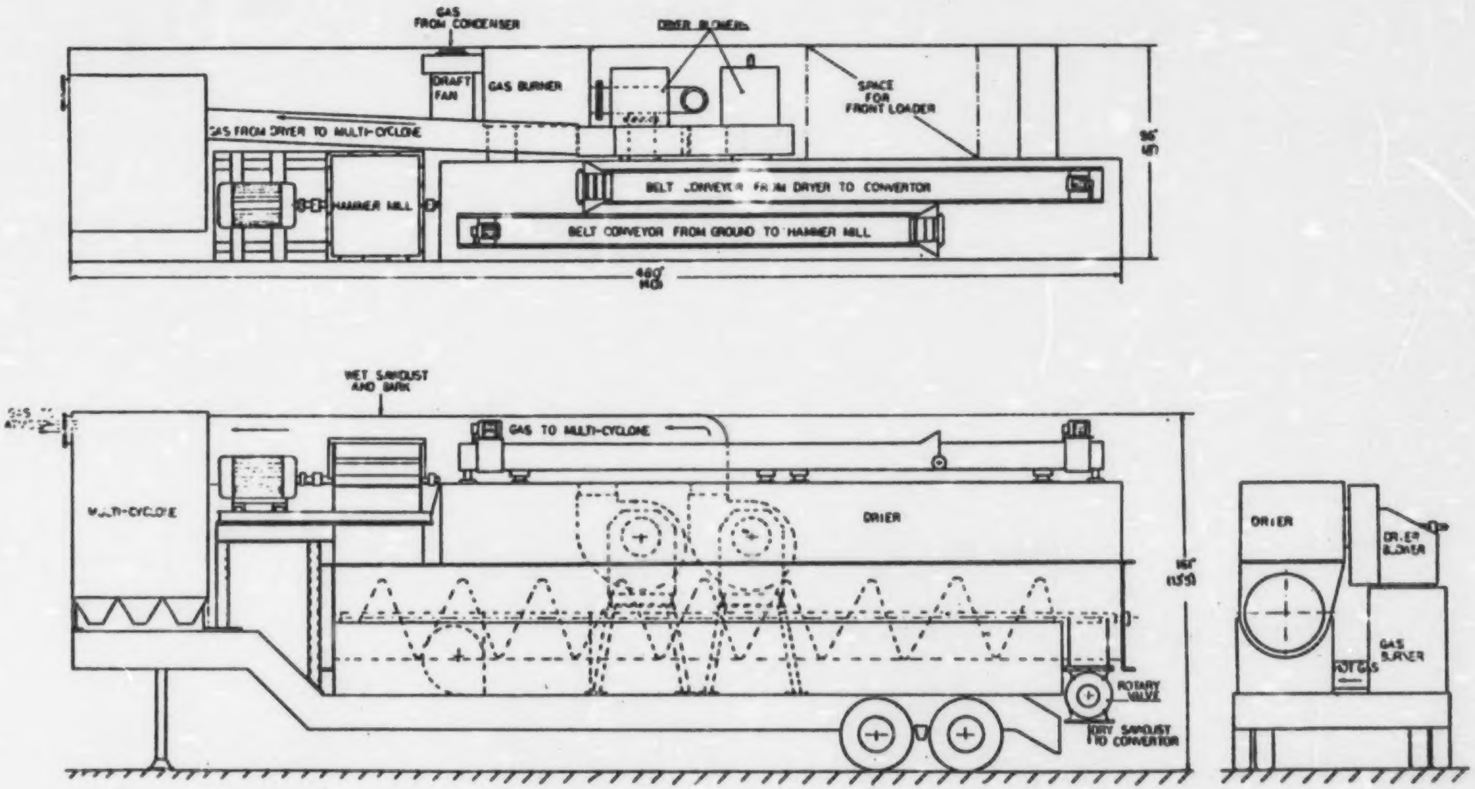
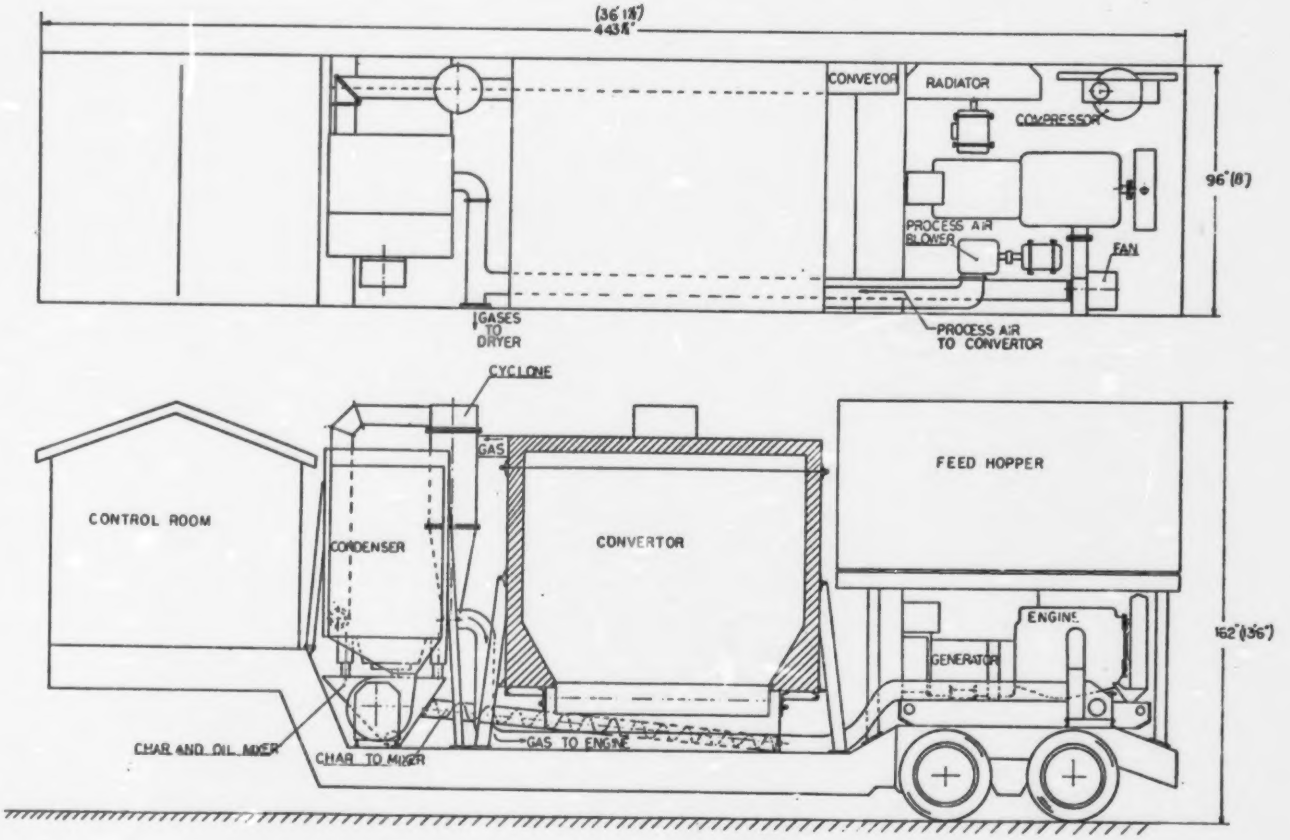
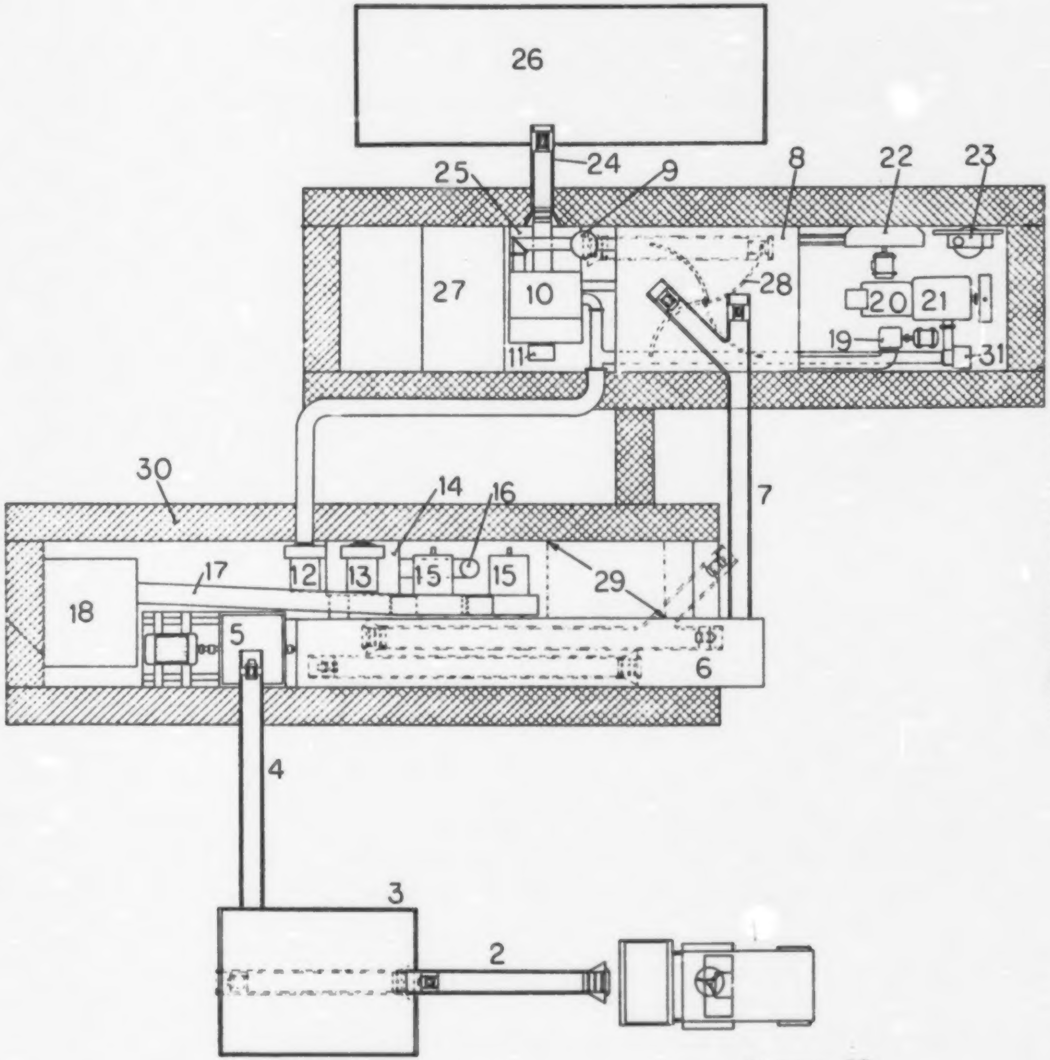

GAS FROM CONDENSER
DRAFT FAN
GAS BURNER
DRIER BLOWERS
SPACE FOR FRONT LOADER
GAS FROM DRYER TO MULTI-CYCLONE
HAMMER MILL
BELT CONVEYOR FROM DRYER TO CONVERTOR
BELT CONVEYOR FROM GROUND TO HAMMER MILL
96"
480"
WET SAWDUST AND BARK
GAS TO MULTI-CYCLONE
MULTI-CYCLONE
DRIER
161"
ROTARY VALVE
DRY SAWDUST TO CONVERTOR
DRIER
DRIER BLOWER
GAS BURNER

Figure 27

Plan and Elevation Views of Trailer II


(36' 11¾")
443¾"
96" (8')
CONVEYOR
RADIATOR
COMPRESSOR
PROCESS AIR BLOWER
FAN
GASES TO DRYER
PROCESS AIR TO CONVERTOR
CYCLONE
GAS
CONTROL ROOM
CONDENSER
CONVERTOR
FEED HOPPER
ENGINE
GENERATOR
162" (13'6")
CHAR AND OIL MIXER
CHAR TO MIXER
GAS TO ENGINE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LEGEND:

1. Front end loader
2. Bin conveyor
3. Receiving bin
4. Conveyor mill
5. Hammer mill
6. Drier
7. Feed conveyor
8. Converter
9. Cyclone
10. Condenser
11. Condenser cooling fan
12. Draft fan
13. Combustion air fan
14. Off-gas burner
15. Drier fans
16. Burner exhaust
17. Drier exhaust duct
18. Cyclone
19. Process air blower
20. Generator
21. Engine
22. Cooling water radiator
23. Compressor
24. Conveyor
25. Char oil mixer
26. Char storage bin
27. Control room
28. Agitator
29. Front end loader storage
30. Cat walk
31. Engine blower

Figure 28

Plan View of Deployed Mobile Pyrolysis System

Figure 29 presents two elevation crossectional views of the pyrolysis unit to be used. Also shown are typical types of agitators that might be employed to increase throughput. In addition, a novel insulating technique, involving the char and feed itself as a means of minimizing heat loss, is shown. The "char shelves" would simply trap a portion of the downward moving waste and then this material because of its relatively low conductivity would resist the passage of heat through the walls. A fibrous, non-ceramic insulator would act as a back-up system. By use of this method of providing an expendable insulator, most of the problems of transporting the unit would be circumvented. In fact this is a key concept in making the entire system transportable.

Finally, Table 7 presents a complete list of components and their characteristics used in the mobile system preliminary design. To illustrate the table, component number 19 (reference Figure 28) is the process air blower, Dresser Model 3514-J, producing 542 cfm at one psig, requiring 3.6 hp and weighing 640 pounds. There are doubtless many other commercially available components which could serve as well as those listed in the table, and therefore the list is for illustrative purposes primarily. However, the table shows that components either commercially available now and/or readily fabricated could be assembled to provide a system with the desired characteristics. Moreover the system size, weight and load distribution would be within the legal limits.

PRELIMINARY ECONOMIC ANALYSIS

The preliminary economic analysis of the portable waste convertor was limited to a study of only one system within an array of systems servicing wood yards and was made on the basis of the current technological development of the system. Assumptions were made, however, regarding the costs of sharing of equipment among systems and the supervision costs of a group of systems. It has been also assumed that by proper scheduling the systems can be kept continuously operating except for down time between waste sites.

Listed below are more detailed assumptions used for the economic analysis of an individual system:

- Interest rates are 9.5 percent
- System costs were computed by scaling-up the actual Cordele facility costs using a 1/2 power law and then multiplying the results by 2.5 to allow for manufacturer profit, inflation and increased complexity of the mobile system. (For a 100 ton/day dry system the costs are about $405,000.)
- A total capital depreciation of ten years is taken
- The mobile unit is assumed to service each waste producer in its circuit once a year

Figure 29

Elevation-Crossection

Views of Mobile Pyrolytic Convertor

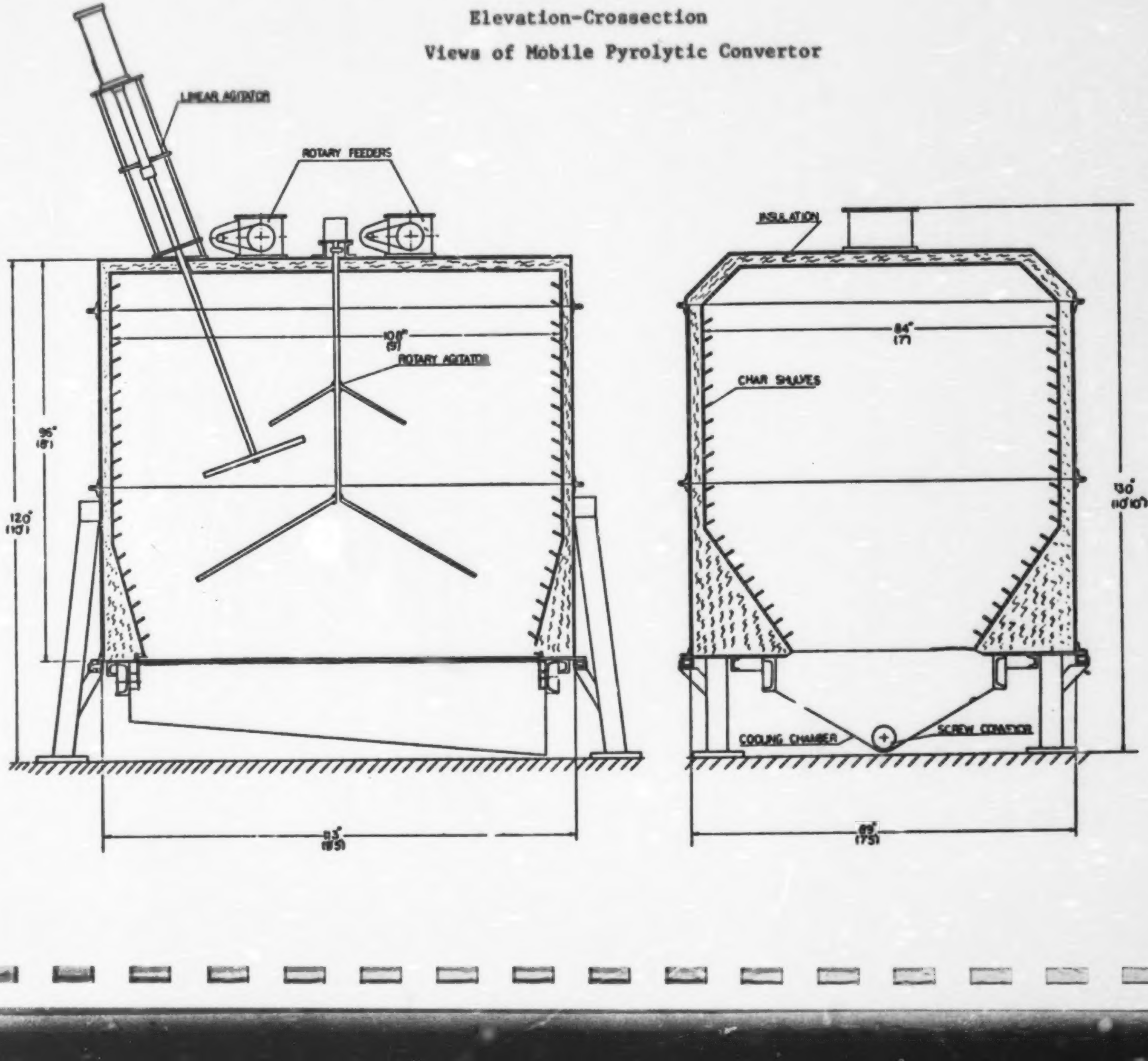

LINEAR AGITATOR
ROTARY FEEDERS
108"
(9')
ROTARY AGITATOR
96"
(8')
120"
(10')
102"
(8.5')
INSULATION
84"
(7')
CHAR SHELVES
130"
(10'10")
COOLING CHAMBER
SCREW CONVEYOR
89"
(7.5')

TABLE 7

LIST OF EQUIPMENT
FOR PORTABLE PYROLYSIS SYSTEM

Part Number	Part Name	Function of the Part	Description	Made By	Model No.	Capacity	H.P.	Weight	Carried On Trailer No.
1.	Front end loader	To load wet feed from ground to bin conveyor.	Tractor-shovel with hydrostatic-drive	International and Hough	H-25B	1 yard of wet feed/ load	N/A	6,200	I
2.	Bin conveyor	To transfer wet feed from front loader to receiving bin.	Belt conveyor: 10' long, 12" wide	Stone	-	8 ton/hour of wet feed	1/2	850	II
3.	Receiving bin	Receives wet feet to feed hammer mill.	Fabricated container including screw conveyor: 10' long, 12" diameter	Fabricated (Link-Belt)	-	320 cubic feet, 8 ton/ hour	1/3	850	II
4.	Hammer mill conveyor	Transfers wet feed from receiving bin to hammer mill.	Belt conveyor: 20' long, 12" wide	Stone	-	8 ton/hour of wet feed	3/4	1,700	I
5.	Hammer mill	Pulverizes feed.	Hammer mill	Williams	C-32	3-5 ton/hour of 2" bark	75	6,000	I
6.	Drier	Drys the wet feed.	Ducting system container, 36" diameter screw conveyor	Link belt & duct work fabricated	-	8 ton/hour of wet feed	1	4,700	I
7.	Feed conveyor	Transfers dry feed from drier to convertor.	Belt conveyor 30' long, 12" wide, 10' long, 12" wide	Stone	-	4 ton/hour of dry feed	1¼	3,400	I
8.	Convertor	Produces char and oil from the dry feed.	See pp. 60 in report	Fabricated	-	4 ton/hour of dry feed	3	22,100	II
9.	Cyclone	Separates the particles from the convertor output gases before entering the condenser.	Dust collector cyclone	Fabricated	-	-	N/A	1,128	II

TABLE 7 (CONTINUED)

Part Number	Part Name	Function of the Part	Description	Made By	Model No.	Capacity	H.P.	Weight	Carried on Trailer No.
10.	Condenser	Condenses the oil in the off-gas from the convertor.	Single-Pass cross-flow	Fabricated	-	N/A	1 x 10 Btu/hr from 500°F to 120°F	5,940	II
11.	Condenser cooling fan	Provides cooling for the oil condenser	Industrial exhauster	American Air Filter	AAF Type K, Adjustible Drive 2 hp motor size 11	1800 c.f.m. at 3" of water pressure drop	1½	195	II
12.	Draft fan	Transfers off-gas from reactor to the off-gas burner.	Industrial exhauster	American Air Filter	AAF Type K, Size 11 Adjustible drive, 5 hp motor	2100 c.f.m. at 10" of water pressure drop	5.02	195	I
13.	Combustion air fan	Supplies air to the off-gas burner burner.	Industrial exhauster	American Air Filter	AAF Type K, Size 19 Adjustible drive, 15 hp motor	10,000c.f.m. at 5" of water pressure drop	12.9	670	I
14.	Off-gas burner	Burns non-condensible off-gas to provide heat for drier.	Horizontal cylindrical burner	Fabricated	N/A	8 ton/hour Gas M=26 from 150°F to 700°F	N/A	5,080	I
15.	Drier fans	Transfers hot combustion gas from off-gas burners through drier and drier cyclone.	2 Industrial exhausters	American Air Filter	AAF Type K, Size 17 x 2 units, Adjustible drive, 20 hp motor	8000 c.f.m. at 10" of water pressure drop	37.4 for two units	1,300	I
16.	Burner exhaust	Exhausts excess combustion gas not required for drying.	Burner stack	PART OF THE BURNER					

TABLE 7 (CONTINUED)

Part Number	Part Name	Function of the Part	Description	Made By	Model No.	Capacity	H.P.	(lb) Weight	Carried On Trailer No.
17.	Drier exhaust duct	Duct from drier to drier cyclone.	Steel duct inlet dimension 12" x 30"	Fabricated	N/A	16,000 c.f.m.	N/A	2,500	I
18.	Drier cyclone	Separates particles from drier exhaust before venting to atmosphere.	Multi-clone	Western-Precipitation	12 VMU Size 8-2	16,000 c.f.m.	N/A	2,300	I
19.	Process air blower	Supplies process air to the convertor.	Roots Whispair Max, rotary positive blower	Dresser	3514-J, Flange mounted drip-proof	542 c.f.m. at 1 psig pressure drop	3.6	640	II
20.	Generator	Supplies electrical power for the unit.	A-C generator 60 cycles	Maraton		120 KW	160	9,000	II
21.	Engine	Drives the generator.	Derated gasoline engine	Waukesha	L1616G	Derated 50 percent	338 at 1800 rpm		II
22.	Cooling water radiator	Provides cooling water for process air tubes.	Flat radiator	General Radiators	-	35 G.P.M.	10	1,300	II
23.	Compressor	Supplies air to pneumatic components.	Automotive air compressor	Champion	VR 3-8	12.8 c.f.m. at 140-170 psi	3	500	II
24.	Output Conveyor	Transfers char and oil from mixer to storage bin.	Belt conveyor, 12" wide, 10" long	Stone	-	2 ton/hour of char & oil	1/3	850	II

TABLE 7 (CONTINUED)

Part Number	Part Name	Function of the Part	Description	Made By	Model No.	Capacity	H.P.	(lb) Weight	Carried On Trailer No.
25.	Char and oil mixer	Mixes the char from the convertor and the oil from the condenser.	Container, screw conveyor 9" diameter 5' long	Fabricated (Link-Belt)	-	4000 lb/hr of material with density of 40 lb/ft	1/4	615	II
26.	Char and oil storage trailer	Stores the oil and char.	Enclosed trailer	Fruehauf	JG9-F2-45 Top close	58,280 lb.	N/A	15,000	-
27.	Control room	Contains operating controls for the unit.	5' x 6' room	Fabricated	N/A	N/A	N/A	1,500	II
28.	Agitator	Prevents bridging in the reactor and promotes uniform flow of material.	PART OF THE CONVERTOR						
30.	Cat Walk	Walking ramp to provide access to system components.	Expanded metal	Fabricated	N/A	N/A	N/A	200 lb for each trailer	I II
31.	Engine blower	Transfers and compresses off-gas fuel to engine.	Roots whispair Max rotary positive blower	Dresser	1704-J Direct coupling drive	115 c.f.m. at 2 psig and 7000 rpm	1.[illegible]	142	II
32.	Trailer I	Carries components: 1, 4, 5, 6, 7, 12, 13, 14, 15, 16, 17, 18, and 30.	25-ton tandem axle level deck load runner, 445" long	Fruehauf	C25L-J2 445" long	50,000 lb	N/A	44,435	-
33.	Trailer II	Carries components: 2, 3, 8, 9, 10, 11, 19, 20, 21, 22, 23, 24, 25, 27, 29, 30, and 31.	25-ton tandem axle level deck load runner, 445" long	Fruehauf	C25L-J2 445" long	50,000 lb	N/A	55,000	-

- The time on site would average two to three weeks, assuming medium size sawmills
- The distance between sawmills is small enough so that the travel time is a minor part of the total down time between sites
- The total down time between sites is two days
- Wood wastes are typically 50 percent water
- If a disposal charge is made, it is $3/ton of raw wastes
- The crew operating the unit comprises a cadre, permanently assigned, and local filler personnel
- The crew has a crew boss who makes $15,000/year and one or more lead men at $12,000/year. The filler personnel make $7,500/year
- It takes two men to operate the unit and there are two or three shifts
- Maintenance is conducted on the weekends
- The system operates 250 days/year
- Supervision overhead is $12,000/year
- Shared equipment expenses are $6,000/year or $9,000/year depending on the number of shifts
- The drier requires 1500 Btu of chemical energy from the non-condensible gas to evaporate each pound of water in the as received feed
- The derated engine operates at 15 percent thermal efficiency. Thus 360 Btu chemical heat energy are required to process one pound of dry feed
- One pound of dry feed produces .456 pounds of char oil mixture including a typical 10 percent moisture fraction
- The heating value of the char-oil mixture is 11,500 Btu/lb. This allows for the 10 percent water fraction

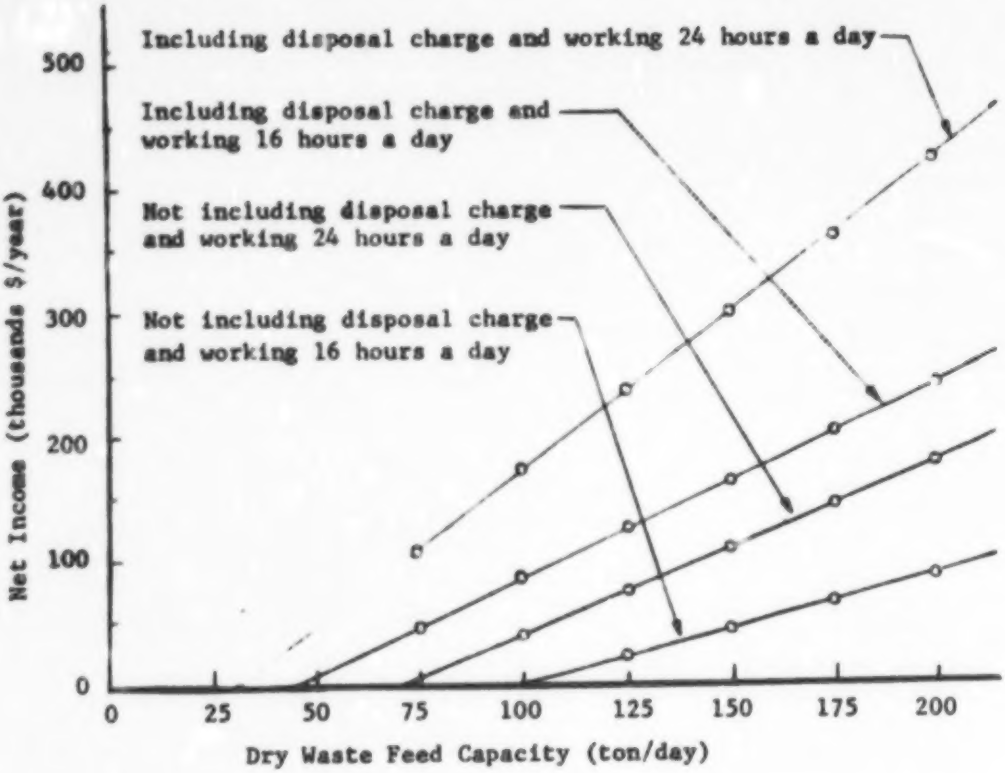
The dominant influence on the results of the analysis is the fuel price which can be obtained for the char-oil mixture. Because so many coal prices are possible, depending upon whether "contract" or "spot market" values are used it was not practical to select just one char-oil fuel price. Therefore three values, i.e., $20/ton, $35/ton, and $50/ton were employed in the analysis. It may be, because of the physical character of the char-oil mixture and because the quantities produced initially will likely not be large, that it is better suited for the spot market which relies heavily on small to medium capacity stoker fixed systems. Communications with stoker manufacturers indicate that the char-oil mixture will burn readily on most stoker systems; in some cases, however, minor modifications to the grate would be required. Likewise there is also the possibility that the mix could be used with packaged boilers, modified with special burners. The low sulfur character of the fuel would be especially important to the small to medium size boiler operator, since flue gas clean-up equipment is proportionately a much higher capital cost item than for large utility boilers. Regardless of the market, the low sulfur character of the fuel should make it more valuable than a high sulfur coal with a comparable heating value.

Thus with all these assumptions the economic analysis[++] was made and the results are presented in Figures 30, 31 and 32, which, for a given fuel cost, show the net income, before taxes, of units as a function of their operating capacity. Parameters investigated are the number of operating shifts and whether or not a disposal credit is charged. These figures together illustrate the dominant influence of the price of the fuel on income and strongly suggest that three shift operation is highly desirable. Likewise it can be seen that the effects of collecting a $3/ton of raw wastes disposal credit can have a significant impact on the net profit. Finally these figures demonstrate the great advantage to be gained in uprating the system capacity.

Figure 33 represents a cross-plot of the data from Figures 30, 31, and 32 for a 100 (dry) ton/day unit, with net income plotted as a function of fuel prices. The figure reinforces the importance of three shift operation to the system economics and again illustrates the influence on profit of a disposal credit. From the figure it appears that even for 16 hr/day operation and without a disposal credit, the break-even point would be $20/ton. And clearly as the fuel price increases, the net income goes up very rapidly.

From this work, it appears that on strictly economic grounds, a strong case can be made for the profitability of the portable waste conversion unit. And when the more intrinsic advantages to society, the environment and our national economics are included, the argument for the development of such a system is compelling.

[++] Presented in Appendix C is a sample calculation from this analysis.



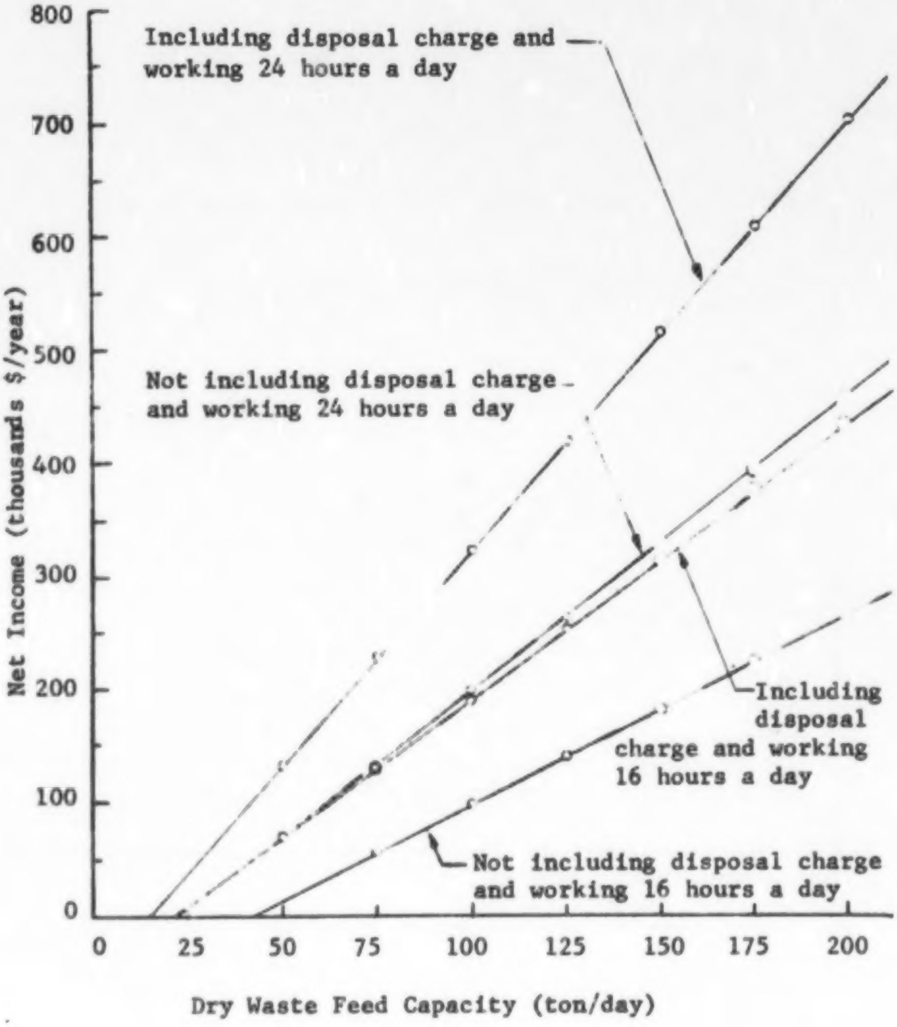
Principal Assumptions:

1. Fuel is worth $20/ton
2. Interest--9.5 percent
3. Depreciation--10 years
4. Raw wastes are 50 percent moisture
5. Disposal charge is $3.00/ton of wet sawdust
6. The results apply to a medium size sawmill

Figure 30

Preliminary Analysis

Net Income of a Mobile Waste Converter with Varying Capacity--Fuel Price $20/ton ($.87/10^6BTU)



Principal Assumptions:

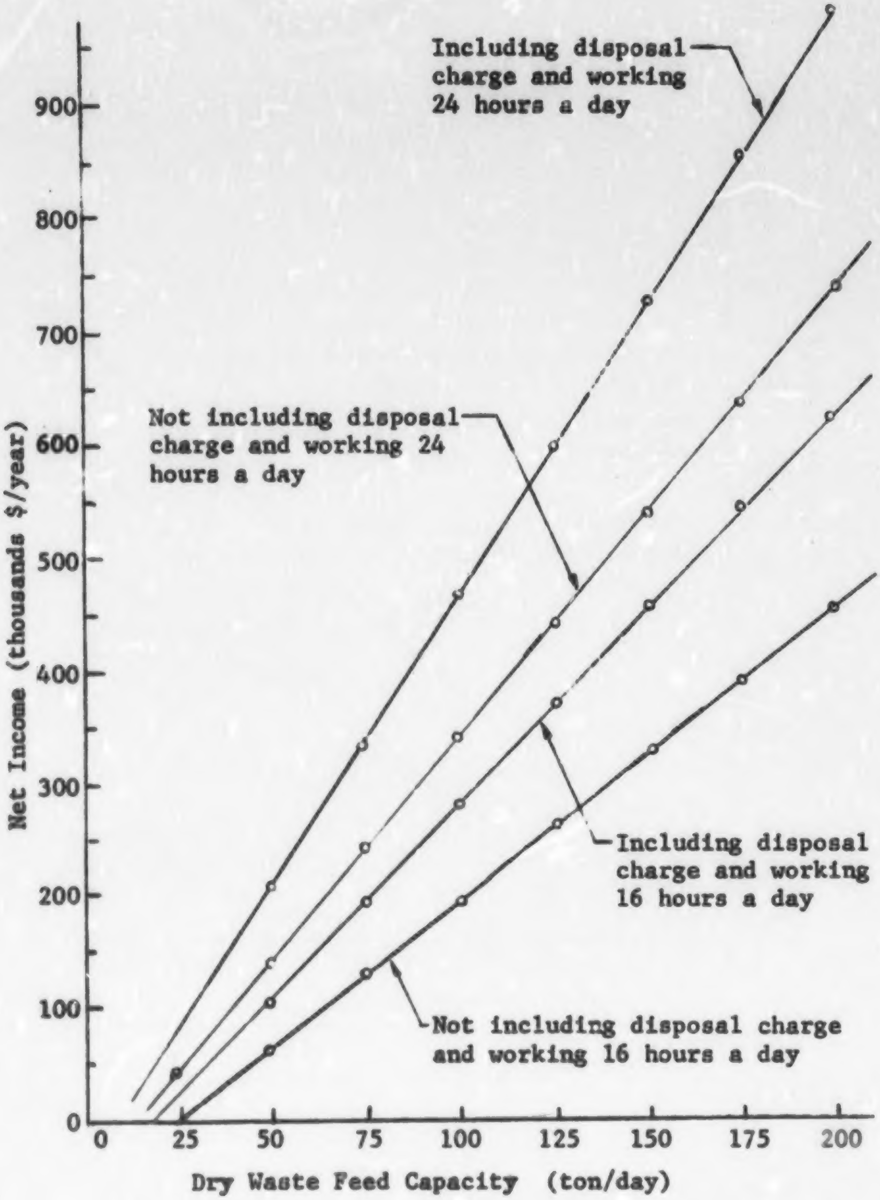
1. Fuel is worth $35/ton
2. Interest--9.5 percent
3. Depreciation--10 years
4. Raw wastes are 50 percent moisture
5. Disposal charge is $3.00/ton of wet sawdust
6. The results apply to a medium size sawmill

Figure 31

Preliminary Analysis

Net Income of a Mobile Waste Convertor

With Varying Capacity--Fuel Price \$35/ton (\$1.52/10^6BTU)

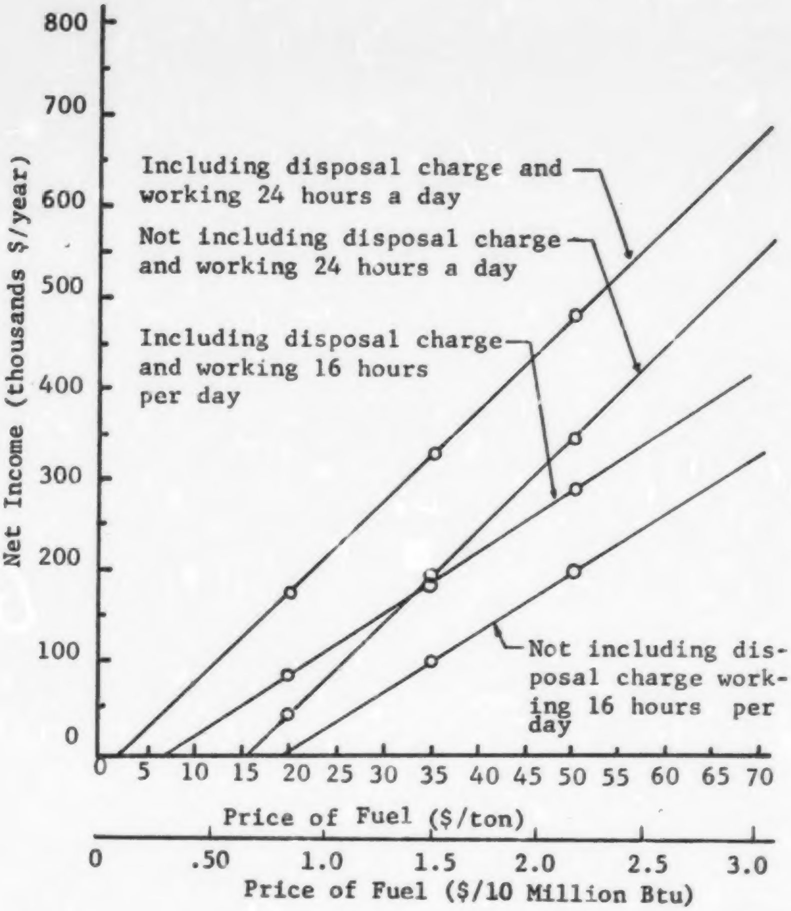


Principal Assumptions:

1. Fuel is worth $50/ton
2. Interest--9.5 percent
3. Depreciation--10 years
4. Raw wastes are 50 percent moisture
5. Disposal charge is $3.00/ton of wet sawdust
6. The results apply to a medium size sawmill

Figure 32
Preliminary Analysis

Net Income of a Mobile Waste Convertor
With Varying Capacity--Fuel Price $50/ton($2.17/10^6BTU)



Convertor with Varying Prices

Principal Assumptions:

1. Interest--9.5 percent
2. Depreciation--10 years
3. Raw wastes are 50 percent moisture
4. Disposal charge is $3.00/ton of wet sawdust

Figure 33

Preliminary Analysis

Net Income of a 100 ton/day (Dry) Waste

SECTION VII

REFERENCES

1. Kemp, Clinton C., Testimony before the Subcommittee on Energy of the Committee on Science and Astronautics, U. S. House of Representatives, Ninety-Third Congress, June 13, 1974.

2. Inman, Robert E. and Allich, John A., Testimony before the Subcommittee on Energy of the Committee on Science and Astronautics, U. S. House of Representatives, Ninety-Third Congress, June 13, 1974.

SECTION VIII

APPENDICES

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C.	Economic Analysis - Sample Calculation for a 100 Ton/Day Unit Working 24 Hours a Day Including Disposal Charge	101
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APPENDIX A

LABORATORY TEST RESULTS

This appendix contains the results of the laboratory tests described in Section V. The data is presented and is discussed in the following order:

- Laboratory analyses for the 14 runs
- Trace element analyses for runs 7 and 15
- Stack emissions
- Viscosity data for pyrolytic oils
- Boiling point data for pyrolytic oil

Laboratory Analyses

Presented in Tables A1-A14 are the routine laboratory analyses of the feed, char, oil, and off-gases used in the heat and mass balances. In most cases at least two values of each parameter were obtained. Attention is especially directed to the footnotes which clarify many of the numbers tabulated.

Trace Element Analyses

Presented in Table A-15 are trace element analyses for runs 7 and 15. In these tests, usually two values were obtained, however, only the average of these is tabulated for the sake of brevity.

Stack Emissions

Stack emissions data for run 17 are presented below:

CO - 10 ppm

SO_2 - 1 ppm

H_2S - 0 ppm

NOx - 1 ppm

The vortex burner was not operating properly during this test and some variations in the CO level were observed.

Presented in Figure A-1 is the viscosity of a typical pyrolytic oil as a function of temperature. As expected the viscosity reduces dramatically with increasing temperature.

Presented in Figure A-2 is a plot of the percent of the oil sample remaining as it is heated from 10°C to 300°C. The smooth, continuous shape of the curve and the lack of any discrete boiling points for the mixture indicates the presence of numerous hydrocarbons.

Table A-1

LABORATORY ANALYSIS

Run 4

Percent Composition	Feed			Char			Oil		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
Water	6.96	7.54	7.25	3.81	4.24	4.03	30.7	-	30.7
Ash	1.13	1.00	1.07	11.01	10.53	10.77	-	-	-
Acid Insoluble Ash	0.24	0.31	0.28	6.94	6.09	6.52	-	-	-
Volatiles	-	-	-	5.29	5.41	5.35	-	-	-
Carbon	46.4	45.0	45.7	79.4	67.3	73.3	47.2	46.5	46.9
Hydrogen	5.7	5.4	5.6	1.1	1.2	1.2	5.9	6.0	6.0
Nitrogen	0.3	0.1	0.2	0.1	0.0	0.1	0.4	0.3	0.4
Oxygen	39.0	38.4	38.7	13.5	13.5	13.5	53.8	41.9	47.9
Heating Value†	7674	7749	7712	11,152	11,523	11,337	-	-	11,900*

Off Gas	
Non-Condensible Components	Percent
N_2	46.7
CO	17.5
CO_2	14.3
H_2	11.8
CH_4	4.3
C_2	0.51
C_3	0.13
C_4	0.03
Heating Value†	2,260*
Molecular Weight**	26.6

† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-2

LABORATORY ANALYSIS

Run 5

Percent Composition	Feed Test 1	Feed Test 2	Feed Average	Char Test 1	Char Test 2	Char Average	Oil Test 1	Oil Test 2	Oil Average
Water	7.81	7.52	7.67	4.07	4.22	4.15	66.3	-	66.3
Ash	1.23	1.14	1.19	4.38	4.12	4.25	-	-	-
Acid Insoluble Ash	0.48	0.56	0.52	1.72	1.53	1.63	-	-	-
Volatiles	-	-	-	-	-	-	-	-	-
Carbon	45.7	45.4	45.6	71.5	71.9	71.7	36.7	37.8	37.3
Hydrogen	5.8	5.8	5.8	3.8	3.6	3.7	7.9	8.0	8.0
Nitrogen	0.4	0.4	0.4	0.0	0.0	0.0	0.2	0.4	0.3
Oxygen	38.7	39.0	38.9	26.6	26.5	26.6	58.2	51.7	55.0
Heating Value[†]	7549	7536	7542	10,166	9,661	9,914	15,900	18,900	15,800[*]

Off Gas Non-Condensible Components	Off Gas Percent
N_2	46.3
CO	21.3
CO_2	15.5
H_2	10.8
CH_4	4.4
C_2	0.54
C_3	0.14
C_4	0.039
Heating Value[†]	2,270[*]
Molecular Weight[**]	27.3

[†] Heating value is in Btu/pound

[*] These values of heating value were calculated from the elemental composition. They were used in the heat balance.

[**] Molecular weight is in pounds/mole

Table A-3

LABORATORY ANALYSIS

Run 6

	Feed			Char			Oil			Off Gas	
Percent Composition	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Non-Condensible Components	Percent
Water	5.20	5.68	5.44	0.60	0.45	0.52	57.6	-	57.6	N_2	36.2
Ash	1.03	0.90	0.97	5.03	4.92	4.98	-	-	-	CO	21.1
Acid Insoluble Ash	0.21	0.30	0.26	1.51	1.77	1.64	-	-	-	CO_2	22.4
Volatiles	-	-	-	22.43	19.44	20.94	-	-	-	H_2	13.2
Carbon	44.9	45.7	45.3	75.8	83.4	79.6	31.9	33.3	32.6	CH_4	6.9
Hydrogen	5.7	5.6	5.7	1.8	1.9	1.9	8.3	7.9	8.1	C_2	1.2
Nitrogen	0.2	0.1	0.2	0.3	1.1	0.7	0.0	0.3	0.2	C_3	0.4
Oxygen	40.9	41.6	41.3	19.5	13.1	16.3	60.3	60.5	60.4	C_4	0.1
Heating Value†	7683	7728	7705	13,138	13,062	13,100	-	-	13,600*	Heating Value†	2,900*
										Molecular Weight**	27.6

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† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-4

LABORATORY ANALYSIS

Run 7

Percent Composition	Feed Test 1	Feed Test 2	Feed Average	Char Test 1	Char Test 2	Char Average	Oil Test 1	Oil Test 2	Oil Average
Water	5.25	5.67	5.44	1.13	1.09	1.11	66.5	-	66.5
Ash	1.39	0.78	1.09	5.88	5.90	5.89	-	-	-
Acid Insoluble Ash	0.43	0.45	0.44	2.80	2.46	2.63	-	-	-
Volatiles	-	-	-	5.35	5.92	5.64	-	-	-
Carbon	45.6	45.8	45.7	88.9	84.8	86.9	44.02	44.1	44.0
Hydrogen	5.6	5.5	5.6	5.9	5.5	5.7	7.44	7.51	7.48
Nitrogen	0.8	0.8	0.8	0.3	0.9	0.6	0.95	0.90	0.92
Oxygen	42.5	42.5	42.5	4.9	8.8	6.8	41.9	45.2	43.6
Heating Value†	7726	7675	7700	13,287	13,208	13,248	-	-	16,300*

Off Gas Non-Condensible Components	Off Gas Percent
N_2	38.6
CO	25.6
CO_2	14.8
H_2	13.2
CH_4	4.82
C_2	0.81
C_3	0.13
C_4	0.02
Heating Value†	2,820*
Molecular Weight**	26.3

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† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-5

LABORATORY ANALYSIS

Run 8

Percent Composition	Feed			Char			Oil		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
Water	6.51	6.19	6.35	1.13	1.04	1.08	57.2	-	57.2
Ash	2.26	2.11	2.18	6.57	6.62	6.59	-	-	-
Acid Insoluble Ash	1.24	1.13	1.18	3.12	3.19	3.16	-	-	-
Volatiles	-	-	-	11.16	10.59	10.87	-	-	-
Carbon	46.7	45.8	46.3	85.6	85.8	85.7	52.7	45.8	49.3
Hydrogen	5.7	5.6	5.7	1.6	1.8	1.7	7.6	8.0	7.8
Nitrogen	0.1	0.0	0.1	0.3	0.8	0.5	0.4	0.7	0.6
Oxygen	41.0	40.1	40.6	5.4	5.4	5.4	40.1	45.8	43.0
Heating Value†	7704	7708	7706	12,994	12,919	12,956	-	-	16,500*

Off Gas	
Non-Condensible Components	Percent
N_2	48.6
CO	14.9
CO_2	18.7
H_2	9.8
CH_4	4.48
C_2	1.69
C_3	0.11
C_4	-
Heating Value†	2,180*
Molecular Weight**	27.9

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

Table A-6

LABORATORY ANALYSIS

Run 9

Percent Composition	Feed Test 1	Feed Test 2	Feed Average	Char Test 1	Char Test 2	Char Average	Oil Test 1	Oil Test 2	Oil Average
Water	6.21	5.88	6.05	1.81	1.69	1.75	60.4	-	60.4
Ash	1.02	1.05	1.04	9.52	9.44	9.48	-	-	-
Acid Insoluble Ash	0.82	0.86	0.84	5.04	5.00	5.02	-	-	-
Volatiles	-	-	-	7.36	7.51	7.44	-	-	-
Carbon	45.3	45.8	45.6	80.6	80.8	80.7	44.1	43.1	43.6
Hydrogen	5.9	5.0	5.5	1.4	1.4	1.4	7.6	7.6	7.6
Nitrogen	0.8	0.2	0.5	0.5	0.1	0.3	0.5	0.2	0.4
Oxygen	46.5	46.8	46.7	9.0	7.2	8.1	47.0	48.2	47.6
Heating Value[†]	7720	7536	7628	12,536	12,542	12,539	-	-	15,700*

Off Gas Non-Condensible Components	Off Gas Percent
N_2	45.2
CO	19.2
CO_2	15.4
H_2	11.5
CH_4	4.4
C_2	0.7
C_3	0.2
C_4	-
Heating Value[†]	2,350*
Molecular Weight**	26.8

[†] Heating value is in Btu/pound

[*] These values of heating value were calculated from the elemental composition. They were used in the heat balance.

[**] Molecular weight is in pounds/mole

Table A-7

LABORATORY ANALYSIS

Run 10

Percent Composition	Feed			Char			Oil		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
Water	5.97	6.09	6.03	2.25	2.33	2.29	70.9	-	70.9
Ash	1.26	1.29	1.28	9.31	9.13	9.22	-	-	-
Acid Insoluble Ash	0.50	0.51	0.51	4.50	4.47	4.49	-	-	-
Volatiles	-	-	-	10.60	11.20	10.90	-	-	-
Carbon	47.3	46.8	47.1	83.9	85.6	84.8	47.7	51.3	49.5
Hydrogen	6.0	5.9	6.0	1.7	1.7	1.7	8.0	7.0	7.5
Nitrogen	0.3	0.2	0.3	0.6	0.7	0.7	0.5	1.3	0.9
Oxygen	43.3	44.6	44.0	6.0	5.4	5.7	46.7	36.6	41.7
Heating Value†	7674	7746	7710	12,290	12,293	12,292	-	-	16,200*

Off Gas	
Non-Condensible Components	Percent
N_2	47.4
CO	19.5
CO_2	12.3
H_2	9.7
CH_4	3.8
C_2	0.47
C_3	0.09
C_4	-
Heating Value†	2140*
Molecular Weight**	27.0

---

† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-8

LABORATORY ANALYSIS

Run 12

Percent Composition	Feed			Char			Oil		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
Water	6.17	6.18	6.18	2.37	2.37	2.37	56.9	-	56.9
Ash	1.12	1.05	1.09	7.41	7.34	7.37	-	-	-
Acid Insoluble Ash	0.23	0.24	0.24	2.41	2.92	2.67	-	-	-
Volatiles	-	-	-	21.99	21.22	21.60	-	-	-
Carbon	46.6	46.4	46.5	81.6	80.6	81.1	41.7	41.7	41.7
Hydrogen	5.9	5.7	5.8	2.4	2.4	2.4	7.9	8.0	8.0
Nitrogen	0.2	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Oxygen	43.5	39.3	41.4	17.7	18.0	17.9	48.4	45.6	47.0
Heating Value†	7715	7663	7689	12,429	12,356	12,393	20,000	19,400	16,600*

Off Gas	
Non-Condensible Components	Percent
N_2	39.5
CO	16.2
CO_2	21.7
H_2	10.2
CH_4	4.76
C_2	0.29
C_3	0.06
C_4	-
Heating Value†	2,010*
Molecular Weight**	28.3

† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-9

LABORATORY ANALYSIS

Run 13

Percent Composition	Feed Test 1	Feed Test 2	Feed Average	Char Test 1	Char Test 2	Char Average	Oil Test 1	Oil Test 2	Oil Average
Water	6.80	6.74	6.77	1.67	1.58	1.63	60.5	63.6	62.1
Ash	1.15	1.14	1.15	5.81	6.07	5.94	-	-	-
Acid Insoluble Ash	0.38	0.36	0.37	2.93	3.16	3.05	-	-	-
Volatiles	-	-	-	34.30	35.[illegible]	34.81	-	-	-
Carbon	46.3	46.3	46.3	75.5	78.0	76.8	44.7	45.2	44.9
Hydrogen	5.8	5.8	5.8	3.2	3.1	3.2	8.4	9.4	8.4
Nitrogen	0.3	0.2	0.3	0.4	0.3	0.4	0.8	0.7	0.8
Oxygen	44.4	46.9	45.6	21.6	20.1	20.9	46.1	45.8	45.9
Heating Value†	7592	7654	7623	11,408	11,456	11,432	16,200	9880	16,800*

Off Gas Non-Condensible Components	Off Gas Percent
N_2	42.8
CO	14.7
CO_2	19.0
H_2	9.2
CH_4	5.2
C_2	0.25
C_3	0.02
C_4	-
Heating Value†	2,050*
Molecular Weight**	28.1

---

† Heating value is in Btu/pound

* These values of heating value were calculated from the elemental composition. They were used in the heat balance.

** Molecular weight is in pounds/mole

Table A-10

LABORATORY ANALYSIS

Run 15

Percent Composition	Feed			Char			Oil		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
Water	3.14	3.74	3.44	1.27	1.09	1.18	61.7	-	61.7
Ash	0.75	0.76	0.76	3.71	3.76	3.74	-	-	-
Acid Insoluble Ash	0.31	0.33	0.32	2.35	2.33	2.34	-	-	-
Volatiles	-	-	-	42.84	43.30	43.07	-	-	-
Carbon	48.6	48.2	48.4	70.4	71.0	70.7	45.9	45.8	45.9
Hydrogen	5.9	5.9	5.9	3.7	4.1	3.9	7.6	7.5	7.6
Nitrogen	0.1	0.3	0.2	0.3	0.4	0.4	0.1	0.1	0.1
Oxygen	46.3	45.2	45.8	27.4	27.0	27.2	46.3	47.8	47.1
Heating Value†	7932	8003	7968	11,125	11,030	11,078	16,700	16,900	16,300*

Off Gas	
Non-Condensible Components	Percent
N_2	36.8
CO	21.7
CO_2	15.1
H_2	10.5
CH_4	5.5
C_2	1.43
C_3	0.39
C_4	0.13
Heating Value†	3,020*
Molecular Weight**	27.1

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

Table A-11

LABORATORY ANALYSIS

Run 16

	Feed			Char			Oil			Off Gas	
Percent Composition	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Non-Condensible Components	Percent
Water	4.45	4.45	4.45	0.95	0.95	0.95	49.7	-	49.7	N_2	44.1
Ash	0.62	0.59	0.61	4.93	4.49	4.71	-	-	-	CO	21.2
Acid Insoluble Ash	0.20	0.21	0.21	3.13	2.62	2.88	-	-	-	CO_2	14.1
Volatiles	-	-	-	2.93	2.93	2.93	-	-	-	H_2	12.7
Carbon	47.3	45.7	46.5	79.4	79.4	79.4	42.1	40.0	41.1	CH_4	4.11
Hydrogen	5.9	5.7	5.8	3.6	3.5	3.6	7.9	6.3	7.1	C_2	1.02
Nitrogen	0.1	0.1	0.1	0.5	0.4	0.5	0.1	0.8	0.5	C_3	0.13
Oxygen	44.3	43.9	44.1	13.8	12.8	13.3	47.2	46.8	47.0	C_4	-
Heating Value†	8117	7986	8052	13,322	13,394	13,358	-	-	14,700*	Heating Value†	2,530*
										Molecular Weight**	26.5

---

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

Table A-12

LABORATORY ANALYSIS

Run 17

Percent Composition	Feed Test 1	Feed Test 2	Feed Average	Char Test 1	Char Test 2	Char Average	Oil Test 1	Oil Test 2	Oil Average
Water	3.92	3.57	3.74	1.16	1.09	1.13	74.1	-	74.1
Ash	0.71	0.73	0.72	7.46	7.25	7.36	-	-	-
Acid Insoluble Ash	0.20	0.22	0.21	5.37	5.40	5.39	-	-	-
Volatiles	-	-	-	49.20	49.99	49.60	-	-	-
Carbon	48.6	47.8	48.2	63.6	62.8	63.2	46.0	44.7	45.4
Hydrogen	5.9	5.5	5.7	4.4	4.4	4.4	7.4	8.2	7.8
Nitrogen	0.1	0.1	0.1	0.2	0.1	0.2	0.8	0.7	0.8
Oxygen	46.1	42.0	44.0	27.1	27.1	27.1	46.2	48.2	47.2
Heating Value†	7999	8017	8008	10,024	9964	9994	-	-	16,300*

Off Gas Non-Condensible Components	Off Gas Percent
N_2	47.9
CO	15.3
CO_2	19.3
H_2	12.6
CH_4	5.30
C_2	0.87
C_3	0.25
C_4	-
Heating Value†	1,960*
Molecular Weight**	27.3

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

Table A-13

LABORATORY ANALYSIS

Run 18

	Feed			Char			Oil			Off Gas	
Percent Composition	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Non-Condensible Components	Percent
Water	5.63	5.90	5.76	2.24	2.22	2.23	64.7	-	64.7	N_2	47.4
Ash	0.49	0.41	0.45	6.51	6.20	6.36	-	-	-	CO	22.2
Acid Insoluble Ash	0.12	0.09	0.11	3.85	3.68	3.77	-	-	-	CO_2	13.4
Volatiles	-	-	-	5.33	5.55	5.44	-	-	-	H_2	11.4
Carbon	47.6	47.4	47.5	88.2	87.9	88.1	50.7	44.4	47.7	CH_4	4.84
Hydrogen	5.8	5.9	5.9	0.9	0.9	0.9	7.4	5.6	6.5	C_2	0.78
Nitrogen	0.4	0.6	0.5	0.8	0.7	0.8	0.3	0.8	0.6	C_3	0.13
Oxygen	45.1	46.3	45.7	14.0	15.2	14.6	43.6	47.3	45.5	C_4	-
Heating Value†	7802	7791	7797	12,735	12,823	12,779	-	-	15,200*	Heating Value†	2,720*
										Molecular Weight**	26.6

---

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

Table A-14

LABORATORY ANALYSIS

Run 19

	Feed			Char			Oil			Off Gas	
Percent Composition	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Non-Condensible Components	Percent
Water	7.29	7.41	7.35	2.20	2.13	2.17	69.8	-	69.8	N_2	51.4
Ash	0.48	0.46	0.47	4.54	4.99	4.77	-	-	-	CO	19.4
Acid Insoluble Ash	0.21	0.19	0.20	2.96	3.41	3.19	-	-	-	CO_2	15.2
Volatiles	-	-	-	36.71	37.56	37.14	-	-	-	H_2	14.3
Carbon	45.4	46.1	45.8	84.1	83.2	83.7	54.5	57.2	55.9	CH_4	4.04
Hydrogen	5.5	5.7	5.6	3.7	3.4	3.6	6.8	6.9	6.9	C_2	1.07
Nitrogen	0.5	0.7	0.6	0.5	0.5	0.5	0.9	0.9	0.9	C_3	0.24
Oxygen	44.8	45.0	44.9	13.3	14.7	14.0	36.8	38.2	37.5	C_4	-
Heating Value†	7718	7712	7715	10,713	10,709	10,711	-	-	16,000*	Heating† Value	2,370*
										Molecular** Weight	26.4

---

†Heating value is in Btu/pound

*These values of heating value were calculated from the elemental composition. They were used in the heat balance.

**Molecular weight is in pounds/mole

TABLE A-15

TRACE ELEMENT ANALYSES

Run Number	Type Sample	Percent Composition									
		Cr	Co	Cu	Fe	Mn	Ni	Zn	V	S	Cl
7	Feed	.005	.004	.010	.39	.10	.008	.024	.29	.0096	.307
7	Char	.017	.016	.028	3.12	.61	.022	.060	.90	.0061	.354
7	Oil	.0017	0	.0004	.57	.0022	.00008	.005	.008	.002	.0071
15	Feed	.007	.002	.005	.26	.14	.008	.035	.09	.0054	.136
15	Char	.022	.005	.017	1.98	.47	.012	.042	.38	.0061	.108
15	Oil	.0017	0	.0005	1.01	.0036	.0002	.003	.010	.0047	.0064

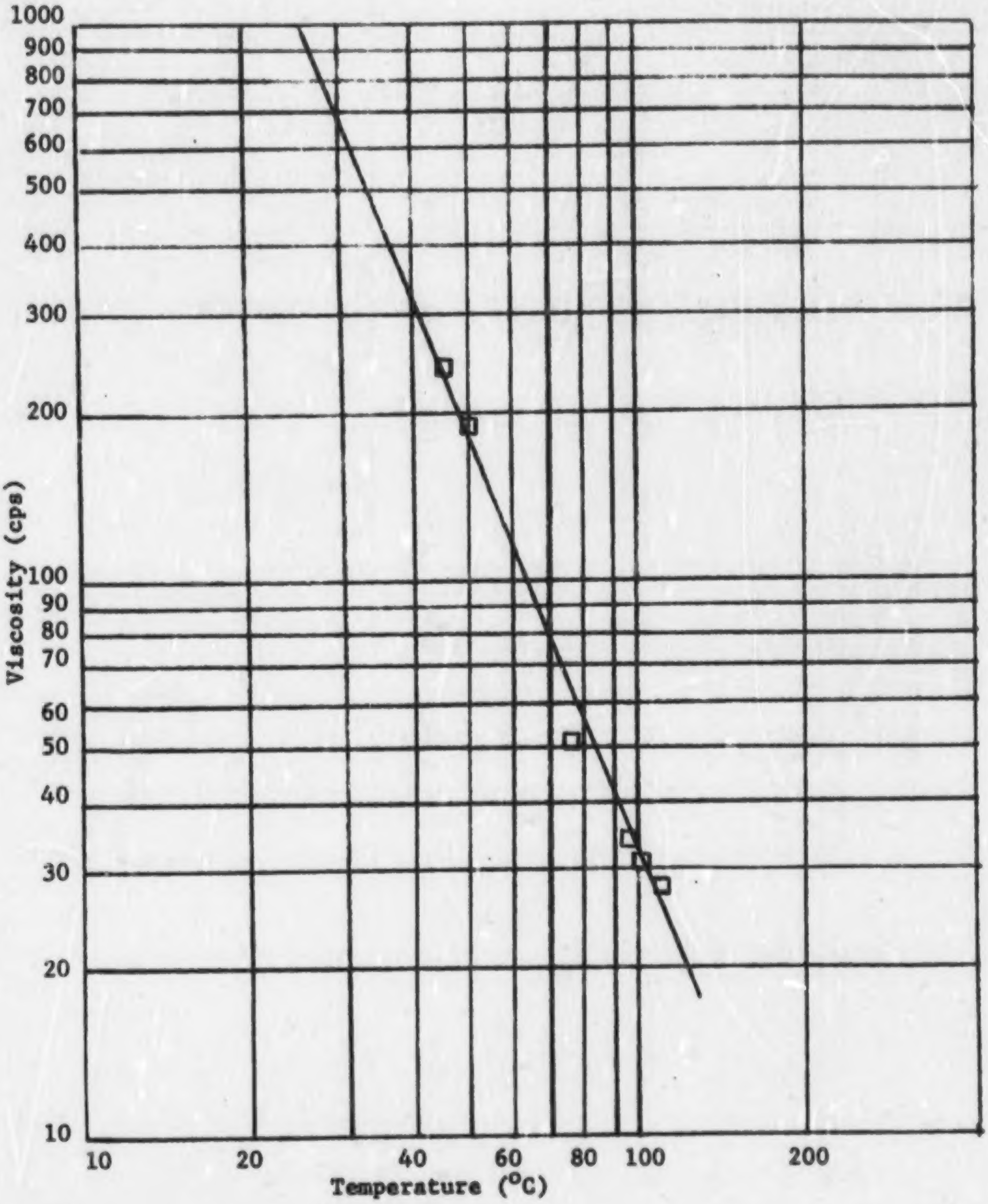

Figure A-1

Viscosity of Pine Waste Pyrolysis Oil

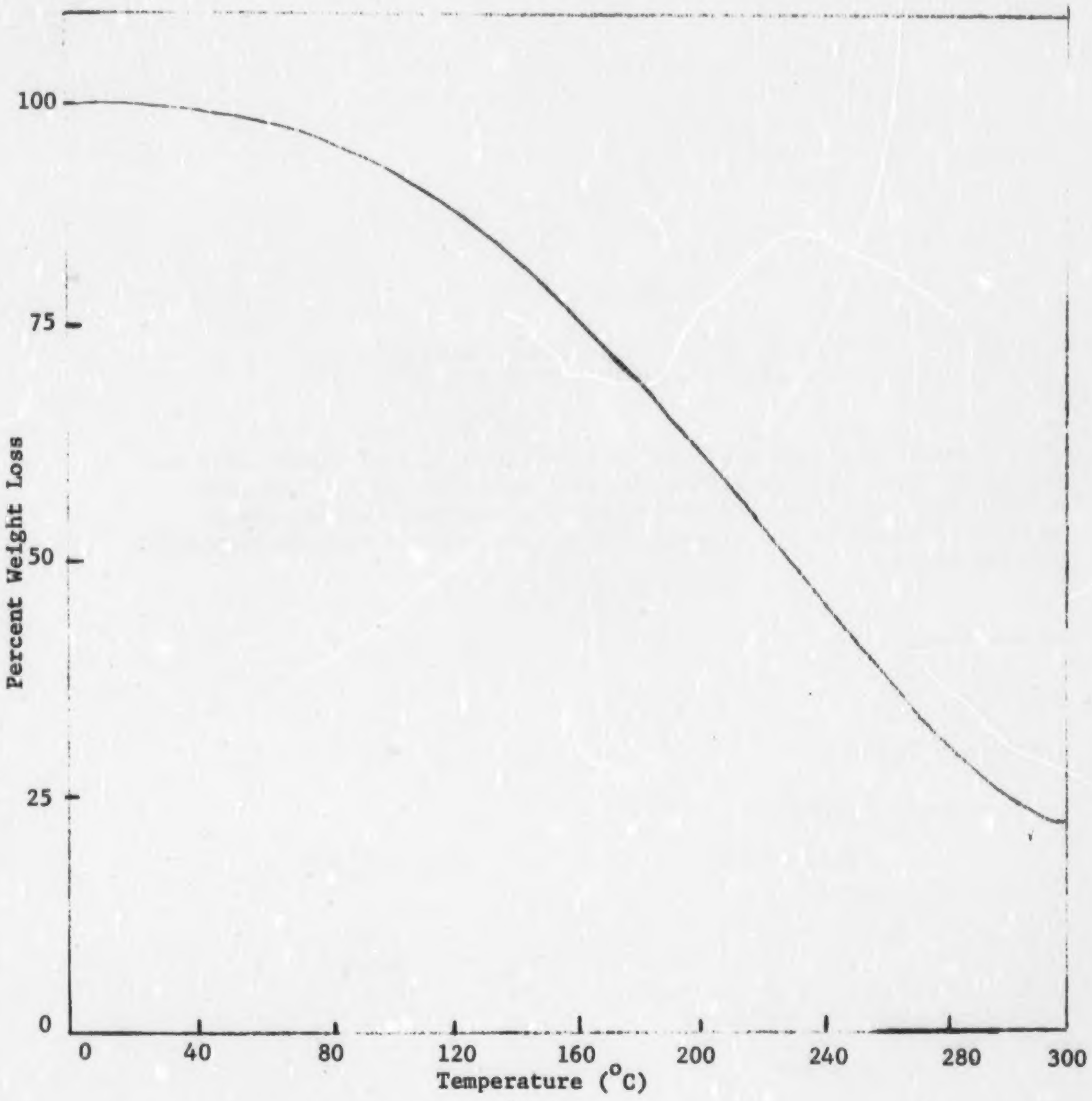

Figure A-2
Weight Loss Versus Temperature
for Pine Wood Waste Pyrolysis Oil

APPENDIX B

SAMPLE CALCULATIONS OF CHEMICAL, MASS AND ENERGY BALANCES USED TO REDUCE TEST DATA

This appendix presents a sample calculation of the chemical, mass and energy balances used to reduce the test data for run 7. The mass balance follows the procedure presented in Figure 18. The energy balance is based on the results of the mass balance and, is relatively straightforward.

MASS BALANCE

Input

Laboratory Analyses -

Feed material (as run).

Composition	Percent (wt)
C	45.7
H_2	5.6
N_2	0.8
O_2 (difference)	42.5
Moisture	5.4

Process Air

Composition	Percent (Vol)
N_2	79
O_2	21

Composition -

Basis 100 pounds dry sawdust processed.

Composition		Weight (lb)
Sawdust		100
Process Air		55.8
Moisture		5.75
	Total	162

Output

Laboratory Analysis -

Char

Composition	Percent (wt)
C	86.9
H_2	5.7
N_2	0.6
O_2 (difference)	6.8
Moisture	1.11

Oil

Composition	Percent (wt)
C	44
H_2	7.48
N_2	0.93
O_2 (difference)	47.6
Moisture	66.5

Gas

Composition	Percent Volume	Corrected to 100% Volume
N_2	38.6	39.4
CO	25.6	26.1
CO_2	14.8	15.1
H_2	13.2	13.5
CH_4	4.82	4.93
C_2	.81	.81
C_3	.13	.13
C_4	.02	.02

Composition -

Basis 100 pounds dry sawdust processed.

Char: Using a moisture content of 1.11 percent; the amount of water and dry char in the 16.3 pounds of recovered char was calculated:

$$16.3(\text{mixture}) \times (1 - .0111) \left(\frac{\text{lb char}}{\text{lb mix}}\right) = 16.1 \text{ lb (char)}$$

$$16.3(\text{mixture}) \times .0111 \left(\frac{\text{lb } H_2O}{\text{lb mix}}\right) = .2 \text{ lb } (H_2O)$$

Oil: The oil was collected and weighed. The amount of dry oil was determined from the lower** of a laboratory determination using the Dean-Stark method or the calculated amount using CHNO analysis.

Analyses	% (wt)	Molecular Wt	mols	Equivalent mols Water	Analysis %
C	44	-	-	-	44.0
H_2	7.48	2	3.74	3.74	1.52
N_2	.93	-	-	-	.93
O_2	47.6	32	1.49	2.98	0
Moisture					53.6

The amount of H_2O from Dean-Stark method was 66.5 percent, therefore the smaller amount was selected or 53.6 percent.

Using this value the amount of dry oil and the amount of water in the recovered 21.8 pounds of oil-water mixture was calculated.

$$21.8 \text{ lb(mixture)} \times (1 - .536) \left(\frac{\text{lb oil}}{\text{lb mix}}\right) = 10.1 \text{ (lb oil)}$$

$$21.8 \text{ lb(mixture)} \times .536 \left(\frac{\text{lb } H_2O}{\text{lb mix}}\right) = 11.7 \text{ (lb } H_2O)$$

Off-Gas -

From the analysis, the molecular weight of the off-gas was calculated:

**The lower value is taken because the oil cannot have any more water than that associated with the oxygen from the CHNO analysis.

Composition	Analysis Corrected to 100 Percent		Molecular Weight	
N_2	39.4	x	28	1100
CO	26.1	x	28	731
CO_2	15.1	x	44	664
H_2	13.5	x	2	27.0
CH_4	4.93	x	16	79
C_2	.83	x	30	25
C_3	.13	x	44	6
C_4	.02	x	58	1
	100 % or mols			2630 lb

$$\text{Average Molecular weight} = \frac{2630 \text{ lb}}{100 \text{ mols}} = 26.3 \text{ lb/mol}$$

To determine the total amount of off-gas produced (per 100 pounds of sawdust) a nitrogen balance was made:

Total nitrogen input (from process air):

$$55.8 \text{ lb(air)} \times \frac{1}{29} \left(\frac{\text{Mols air}}{\text{lb}}\right) \times .79 \left(\frac{\text{Mols } N_2}{\text{Mol air}}\right) = 1.52 \text{ (mols } N_2\text{)}$$

Mols of off-gas

$$\frac{1.52 \text{ (mols } N_2\text{)}}{.394 \left(\frac{\text{mols } N_2}{\text{mol off-gas}}\right)} = 3.85 \text{ mols off-gas}$$

Total weight of off-gas is:

$$3.85 \text{ (mols)} \times 26.3 \left(\frac{\text{lb}}{\text{mol}}\right) = 102 \text{ lb (off-gas)}$$

Water: The amount of water in the off-gas was determined by a hydrogen balance.

Input H_2

Sawdust	5.9 (lbH_2)
H_2O	.64 (lbH_2)
	6.54 (lbH_2)

Output H_2

Char: 16.3 (.057) = .93 lb H_2
Oil: 21.8 (.0748) = 1.63 lb H_2

off-gas

	$\frac{\text{mol } H_2}{\text{mol off-gas}}$
H_2	.135
CH_4	.0986
C_2	.0249
C_3	.0052
C_4	.001
	.2647 $\frac{\text{Total mols } H_2}{\text{mol off-gas}}$

$$.2647 \left(\frac{\text{mols } H_2}{\text{mols off-gas}}\right) \times 3.85 \text{ (mol off-gas)} \times 2 \frac{\text{lb}}{\text{mols}} = 2.04 \text{ lb } H_2$$

Total output = 4.60 lb H_2

Input - Output = lb H_2 associated with water in off-gas

$$6.54 \text{ lb } H_2 - 4.60 \text{ lb } H_2 = 1.94 \text{ lb } H_2$$

$$1.94 \text{ lb } H_2 \times \frac{1}{2} \frac{\text{mol } H_2}{\text{lb } H_2} \times \frac{1 \text{ mol } H_2O}{1 \text{ mol } H_2} \times \frac{18 \text{ lb } H_2O}{1 \text{ mol } H_2O} = 17.5 \text{ lb } H_2O$$

Total water is the sum of water in off-gas, oil and char:

$$17.5 + 11.1 + .2 = 28.8 \text{ lb } H_2O$$

The total mass accounted for in the output is the sum of the char, oil, off-gas, and water:

$16.1 + 10.1 + 102 + 28.8 = 157$

Oxygen Balance: An oxygen balance was made as a check on the amount of water in the off-gas.

Input:

Sawdust:

$$100 \text{ (lb sawdust)} \times .425 \left(\frac{\text{lb } O_2}{\text{lb sawdust}}\right) = 42.5 \text{ (lb } O_2\text{)}$$

Water in feed:

5.75 lb H_2O is equivalent to 5.1 lb O_2

Process Air:

$$55.8 \text{ lb air} \times \frac{1}{29} \left(\frac{\text{mols air}}{\text{lb}}\right) \times .21 \frac{\text{mol } O_2}{\text{mol air}} \times 32 \left(\frac{\text{lb } O_2}{\text{mol}}\right)$$

$$= 12.9 \text{ lb } O_2$$

Total input: $42.5 + 5.1 + 12.9 = 60.5$

Output:

Char: (including associated moisture)

$$16.3 \text{ lb} \times .068 \left(\frac{\text{lb } O_2}{\text{lb Char}}\right) = 1.11 \text{ lb } O_2$$

Oil: (including associated moisture)

$$21.8 \text{ lb} \times .476 \left(\frac{\text{lb } O_2}{\text{lb oil}}\right) = 10.4 \text{ lb } O_2$$

Water: (not in oil or char)

$$14.8 \text{ lb} \times .889 \left(\frac{\text{lb } O_2}{\text{lb water}}\right) = 13.2 \text{ lb } O_2$$

Off-Gas: (dry)

$$\frac{\text{mols } O_2}{\text{mols off-gas}}$$

	$\frac{\text{mols } O_2}{\text{mols off-gas}}$
CO	.1305
CO_2	.151
	.282 $\left(\frac{\text{total mols } O_2}{\text{mols off-gas}}\right)$

$$.2815 \frac{\text{mols } O_2}{\text{mols off-gas}} \times 3.85 \text{ (mols off-gas)} \times \frac{32 \text{ lb } O_2}{\text{mols } O_2} = 34.7 \text{ lb } O_2$$

Total output O_2 is the sum of the amounts from char, oil, water and off-gas. The amount unaccounted for is the difference between input and output:

$$60.5 - 59.4 = 1.1 \text{ lb } O_2$$

A carbon balance was made to account for oil lost due to inefficiency of the condenser and some leakage in the system.

Input:

Sawdust: 100 lb x .482 lb C = 48.2 lb C

Output:

Char: 16.3 x .869 = 14.2 lb C

Oil: 21.8 x .440 = 9.59 lb C

Off-Gas: From off-gas analysis the amount of carbon in the gas is calculated:

Composition	$\frac{\text{mols } O_2}{\text{mols off-gas}}$	
CO	.261	
CO_2	.151	
CH_4	.049	
C_2	.017	
C_3	.004	
C_4	.001	
	.483	$(\frac{\text{total mols C}}{\text{mol off-gas}})$

$$.483 \frac{\text{mols C}}{\text{mol off-gas}} \times 3.85 \text{ mols off-gas} \times \frac{12 \text{ lb C}}{\text{mol C}} = 22.3 \text{ lb C}$$

The total output of carbon is the sum of the carbon in the char, oil, and off-gas:

$$14.2 + 9.59 + 22.3 = 46.1 \text{ lb}$$

The difference between the input and output represents the "lost carbon."

$$48.2 - 46.1 = 2.1 \text{ pounds}$$

Total output, then is the sum of the char, oil, off-gas, water and lost carbon.

16.1 lb char + 10.1 lb oil + 102 lb off-gas + 28.8 lb H_2O

+ 2.1 lb "lost" carbon = 159 lb

The amount of mass unaccounted for = 162 - 159 = 3 lb.

The percentage mass balance error is

$$\frac{3}{162} \times 100 = 1.9\%$$

ENERGY BALANCE

Basis: 100 pounds dry sawdust, reference: 70°F, off-gas temperature: 300°F, char temperature: 1101°F, ΔT cooling water - 10°F.

Input

From laboratory data the heating value of dry sawdust feed is 8139 Btu/lb. Therefore the total heat was obtained by:

100 lb x 8139 Btu/lb = 914,000 Btu

Output

From the mass balance 16.1 lb char, 10.7 lb of oil, 102 lb of off-gas, and 28.8 lb of water were produced.

The heating value of the char was determined directly in the laboratory to be 13,400 Btu/lb. The heating value of the oil and the off-gas was calculated from the constituent determinations to be 16,300 Btu/lb and 2820 Btu/lb respectively. The heat content of the water was determined from the steam tables. Then the chemical energy was obtained by multiplying the heating value of the product times the weight produced.

16.1 lb char x 13,400 Btu/lb = 216,000 Btu
10.7 lb oil x 16,300 Btu/lb = 172,000 Btu
102 lb off-gas x 2820 Btu/lb = 288,000 Btu
2.1 lb "lost" carbon x 14,500 Btu/lb = 30,500 Btu

Latent and sensible energy was calculated from the data as follows:

28.8 lb (water) x 1142 Btu/lb = 32,900 Btu
102 lb (off-gas) x .2 Btu/lb °F x (300°F - 70°F) = 4690 Btu
16.1 lb (char) x 3 Btu/lb °F x (1101 °F - 70°F) = 4980 Btu
10.7 lb (oil) x 200 Btu/lb = 2140 Btu

Heat lost in cooling air tubes:

$$2008 \text{ lb} \times 1 \text{ Btu/lb °F} \times 10\text{°F} = 20{,}000 \text{ Btu}$$

The convective loss from the system was estimated to be:

$$100 \text{ ft}^2 \text{ (1) Btu/ft}^2\text{°F} \times 650\text{°F} = 6500 \text{ Btu}$$

The total output energy is the sum of all these energies which is equal to 778,000 Btu. Therefore:

$$\text{Input Energy} - \text{Output Energy} = 814{,}000 - 778{,}000 = 36{,}000 \text{ Btu}$$

Percentage error in Energy Balance is

$$\frac{36{,}000}{814{,}000} \times 100 = 4.42\%$$

APPENDIX C

ECONOMIC ANALYSIS

SAMPLE CALCULATION FOR A 100 TON/DAY UNIT WORKING 24 HOURS A DAY INCLUDING DISPOSAL CHARGE

Inputs:

a. The capacity of the unit is 100 ton/day dry sawdust
b. The unit is in operation 24 hr/day 250 days/year
c. Fuel is worth $35 per ton
d. Interest rate is 9.5 percent
e. Depreciation of the unit is 10 years
f. Raw wastes are 50 percent moisture
g. Disposal charge is $3.00/ton of wet sawdust
h. The results apply to a medium size sawmill
i. 45.6 percent charcoal and oil can be obtained from the dry sawdust

Utilization Factor:

Utilization factor (η) is the ratio between the production time and the total time.

Total Time includes:

a. Production time (PT), which is the average time in which the unit operates at each sawmill. This is found by dividing the amount of sawdust that a medium size sawmill produces by the capacity of the unit.

b. Starting time (ST), which is the average time interval from arrival at the sawmill to the time the unit operates.

c. Turn-off time (TOT), which is the average time interval between the time the unit stops and the time that the unit is back on the road.

d. Traveling time (D/ν), which is the average time that it takes to travel from one sawmill to another. It is found by dividing the average distance between two sawmills (D) by the average speed that the unit travels (ν).

so:

$$\eta = \frac{PT}{PT + ST + TOT + D/\nu}$$

The total of starting time, turn-off time and traveling time is approximately two days in Georgia.

so:

$$ST + TOT + D/\nu = 2$$

and:

$$\eta = \frac{PT}{PT + 2}$$

Production time (PT) is the production rate of sawdust per year divided by the capacity of the unit (CAP).

$$\eta = \frac{\frac{PR}{CAP}}{\frac{PR}{CAP} + 2} = \frac{PR}{PR + 2 \times CAP}$$

or:

$$\text{utilization factor} = \frac{\text{Average production of a sawmill per year (TONS)}}{\begin{array}{l}\text{capacity of} \\ \text{the unit} \\ \text{(ton/day)}\end{array} \times \begin{array}{l}\text{time interval} \\ \text{between turning} \\ \text{off the unit} \\ \text{and starting it} \\ \text{again at the} \\ \text{next sawmill (day)}\end{array} + \begin{array}{l}\text{Average production} \\ \text{of a sawmill per} \\ \text{year (ton)}\end{array}}$$

The production rate of sawdust by a medium size sawmill is approximately 3,000 ton/year.

So the utilization factor for a 200 ton/day unit is:

$$\eta = \frac{3000}{200 \times 2 + 3000} = 0.89$$

Income:

The income per year, including disposal charge, is a function of: capacity of the unit, number of shifts a day that the unit operates, the amount of oil and charcoal that can be obtained from the dry sawdust, utilization factor, number of days per year that the unit operates, and the value of the fuel.

$$\frac{\text{Income}}{\text{year}} = \left[\begin{array}{l}\text{Capacity of}\\ \text{the unit}\\ \text{dry ton/day}\end{array} \times \begin{array}{l}\text{Utilization}\\ \text{factor}\end{array} \times \begin{array}{l}\text{Number working}\\ \text{days per year}\end{array} \times \begin{array}{l}\text{percent charcoal}\\ \text{and oil obtained}\\ \text{from the dry}\\ \text{sawdust}\end{array}\right.$$

$$\left. \times \ \text{price of fuel}\right] + \left[\begin{array}{l}\text{capacity of}\\ \text{the unit wet}\\ \text{ton/day}\end{array} \times \begin{array}{l}\text{number}\\ \text{working}\\ \text{days}\\ \text{per year}\end{array} \times \begin{array}{c}\text{disposal}\\ \text{charge}\end{array} \times \begin{array}{c}\text{utilization}\\ \text{factor}\end{array}\right]$$

$$\frac{\text{Income}}{\text{year}} = \left[100\ \frac{\text{ton}}{\text{day}} \times 0.89 \times 250\ (\text{days}) \times \frac{45.6\%}{100} \times 35\ \left(\frac{\$}{\text{ton}}\right)\right] + \left[200\ \frac{\text{ton}}{\text{day}}\right.$$

$$\left. \times\ 0.89 \times 250\ (\text{days}) \times 3\ \left(\frac{\$}{\text{ton}}\right)\right] = \$488{,}610 \text{ per year.}$$

Costs:

The different costs of the unit per year are: labor, overhead, depreciation, interest and maintenance.

First shift group: includes one worker who earns $15,000 per year. He is the foreman of the whole crew. There is also a helper who earns $7,500 per year.

Second and third shift group: includes one worker who earns $12,000 pear year. He is the leadman of the shift. There is also a helper who earns $7,500 per year.

Driver: one driver for each shift who earns $12,000 per year and serves four units.

Overhead: overhead for each unit is $12,000 per year. It covers cost at the headquarters for a manager, secretary and office space. Such an office headquarters serves ten units or more.

Depreciation: depreciation cost assumes the life time of the unit to be 10 years with no value afterwards. The interest rate is nine and one-half percent payable over 10 years. The cost of the unit as a function of capacity is found by using the relation

$$\text{Cost of Unit} = 40{,}500\ (\text{capacity})^{1/2}$$

The cost of a 100 ton/day unit is then $405,000.

The annual payment for the unit is $64,504.

The maintenance cost is $11,000 per year. It includes cost of parts to be changed and covers the cost of a maintenance crew that services four units. The total operating cost for a 100 ton/day unit is $158,004 per year.

Net Income:

The net income not including tax is the difference between the total income and the total cost,

so:

Net Income per year = $488,610 - $158,004 = $330,600 per year

APPENDIX D

UNIT CONVERSION TABLE

English Unit	Conversion	Metric Unit
Btu	multiply by 1.055×10^{3} to obtain	joules
Cfm	multiply by 4.72×10^{-4} to obtain	meters ^{3}/sec
ft	multiply by 3.048×10^{-1} to obtain	meters
°F	subtract 32 and divide by 1.8 to obtain	°C
hp	multiply by 7.457×10^{2} to obtain	watts
hr	multiply by 3600 to obtain	seconds
inch	multiply by 2.54×10^{-2} to obtain	meters
inch of water	multiply by 2.458×10^{-3} to obtain	atmospheres
lb	multiply by 4.536×10^{-1} to obtain	kilogram
minute	multiply by 60 to obtain	seconds
psig	multiply by 6.804×10^{-2} to obtain	atmospheres
ton	multiply by 9.0718×10^{2} to obtain	kilogram